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GEOTECHNICAL AND LEACHING PROPERTIES OF FLOWABLE FILL INCORPORATING WASTE FOUNDRY SAND

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Abstract: Waste foundry sand (WFS) can be converted into flowable fill for geotechnical applications. In this study, WFS samples were obtained from 17 independent metal casting facilities with different casting processes. Thus, the WFS samples used in this study represented a good range of WFS properties. The laboratory studies include physical, geotechnical and leaching properties of flowable fills consisting of WFS, cement, and fly ash mixed to different water contents. The main properties measured include WFS physical properties (density, particle gradation, grain shape and fine content), WFS flowable fill geotechnical properties (unconfined compressive strength, hydraulic conductivity, setting time, and bleeding), and the fill's leaching properties (heavy metals contents and organics in the bleed water and the leachate extracted from hardened WFS flowable fill). The test results indicate that in terms of the physical properties, most of the data fall within narrow ranges, although data from the copper/aluminum-based WFS samples might fall beyond the ranges. Geotechnical properties of WFS flowable fills in both fresh and hardened phases are verified conforming to features of specified flowable fills. In terms of leaching properties, the analyses of the bleed water and leachate of WFS flowable fills indicate that the toxicity of WFS flowable fills is below regulated criteria. A mix formulation range derived from this study is proposed for the design of WFS made flowable fill.

Keywords: flowable fill, hydraulic conductivity, leaching properties, physical properties, unconfined compressive strength, waste foundry sand.

Introduction

Metal casting foundries in the US disposed of approximately 9 million metric tons of waste foundry sand (WFS) in landfills in 2000 (Winkler and Bol'shakov, 2000). Given the national average tipping fee of foundry byproducts to landfills at US$ 15-75 per ton inclusive of storage, transportation and labor costs (Winkler et al., 1999), the annual expense of WFS disposal was around US$ 135-675 million. The considerable disposal expense has made the current practice of WFS disposal in landfills less favorable. Besides the financial burden to the foundries, landfilling WFS also makes them liable for future environmental costs, remediation problems, and regulation restrictions. This issue is increasingly addressed by alternate scenarios of beneficially reusing WFS. Beneficial reuses of WFS span a variety of applications related to infrastructure engineering and rehabilitation works, e.g., highway embankment construction (Ham et al., 1990; Javed and Lovell, 1994a, 1994b; Mast and Fox, 1998; Kleven et al., 2000; Abichou et al., 2004), ground improvement (Vipulanandan et al., 2000), concrete (Naik et al., 1994, 2003), flowable fill (Bhat and Lovell, 1996, 1997; Naik et al., 1997a, 1997b, 2001; Tikalsky et al., 1998, 2000; Dingrando et al., 2004), hydraulic barrier or liner (Abichou et al., 2000, 2002, 2005; Goodhue et al. 2001). These alternate applications offer cost savings for both foundries and user industries, and an environmental benefit at the local and national level.

Flowable fill, also termed controlled low-strength material (CLSM) by ACI (1999), is a self-compacted, cementitious geomaterial used primarily as a backfill in lieu of compacted fills for a variety of geotechnical work, e.g., conduit bedding and covers, retaining wall backfills, and abandoned tank or cavity fills. Engineering features of this geomaterial include being self-leveling and self-compacted with minimal effort in its fresh phase, being self-set with maximum unconfined compressive (UC) strength of 8.3 MPa. Flowable fill is often proportioned to develop strengths much less than the limit to allow for future excavation, e.g., 0.86 MPa at day 28 for Type A and B flowable backfills as defined by US Pennsylvania Department of Transportation (US PennDOT, 2003). Depending upon the UC strength and density, US PennDOT (2003) also defines the other two types of flowable fills: Type C non-excavatable flowable fill having 28-day UC strength over 5.51 MPa, and Type D low-density flowable fill.

Use of flowable fill is a growing market that meets the basic technical and economic qualifications to address a beneficial reuse program of WFS. Components of flowable fill generally consist of cementitious materials (cement and fly ash), fine aggregates (granular sand and fly ash), water, and/or chemical admixtures in proportions. The components may vary or be replaced only if technically specified features by ACI (1999) in both fresh and hardened phases are attained, i.e., flowability, segregation, setting time, hydraulic conductivity, and strength gains. WFS can be substituted for fine aggregate in flowable fill matrix (Bhat and Lovell, 1996, 1997; Naik et al., 1997a, 1997b, 2001; Tikalsky et al., 1998, 2000). The use of WFS as a major component in flowable fill not only promises high volume WFS utilization, diverts WFS from landfillings, but also saves the exploitation of natural granular sand and avoids the use of scarce raw resources. Therefore, the economic advantage of beneficially reusing WFS in flowable fill makes it competitive against conventional flowable fills.

To secure a better understanding about both geotechnical and leaching properties of excavatable WFS flowable fill is the primary goal of this study. Previous studies (Bhat and Lovell, 1996, 1997; Naik et al., 1997a, 1997b, 2001; Tikalsky et al., 1998, 2000; Dingrando et al., 2004) investigated the geotechnical properties of WFS flowable fills using single or multiple (up to 3 or 4) WFS sample sources and obtained promising findings. A wider selection of WFS samples, representing a better range of WFS properties, may further encourage the reuse of WFS in flowable fill, as recommended by Naik et al. (2001). In addition, WFS flowable fill's leaching properties, i.e., contaminant types and concentrations in discharge channels of bleed water and leachate, help assess the environmental impact of materials and qualify WFS as a component in flowable fill from an environmental prospective. In this study, an effort was made to verify both geotechnical and leaching properties of excavatable flowable fills containing various WFS samples through a laboratory testing program.

Testing program

Materials

WFS, cement, fly ash and water are materials blended to produce flowable fills. WFS samples (WFS01 to WFS17 in Table 1) were obtained from 17 independent foundry facilities using varying casting processes. Table 1 summarizes each sample's casting background, including casting metal types (iron, steel, aluminum and copper), binders (bentonite, phenolic urethane and furfural alcohol, etc.), and binding systems (green sand, shell and no-bake, etc.). Iron and bentonite related WFS samples have the highest incidence among investigated samples, which represents the variation of casting processes current used in the foundry industry. Class F fly ash and Type I cement, conforming to ASTM C618-03 and C150-02, respectively, were supplied by commercial sources. Potable tap water at room temperature (23 ºC) was used in all phases of experimentation.

Testing methods

Three aspects were researched about the qualification of WFS-based flowable fills, i.e., its physical, geotechnical and leaching properties. WFS particle gradation, grain shapes, fine contents, density, absorption and specific gravity, WFS flowable fill's flowability, bleeding, setting time, UC strength gains, hydraulic conductivity and leaching characteristics were evaluated.

WFS physical properties help recognize the workability and suitability of WFS in flowable fill. Particle gradation, grain fineness number (GFN) and grain shape, are important determinants of flowability, compacted density and strength of a WFS mixture (Carey and Sturtz, 1995). Standard testing protocols of these properties are summarized in Table 2. Particle gradation was investigated by a sieve analysis according to AFS 1105 standard "sieve analysis (particle size determination of sand)" specified by AFS (2000). Through sieving, a WFS sample was separated into ten segments by specified size ranges. The grain shape of each segment was observed by using a 20× optical microscope according to AFS 1107 standard "grain shape classification" to characterize WFS grain shape according to gradation. One or two grain shapes with mass percentage over 50% were regarded as the predominant shape(s) for a WFS sample. GFN, a measure of the average grain size of an aggregate, was determined based on the number of sieve openings per inch of a sieve which would just pass the average size calculated from the sieve analyses according to AFS 1106 standard “grain fineness number, AFS GFN”. The greater the GFN, the finer the average grains. Absorption indicates the process by which a liquid is drawn into the WFS matrix and fills pore space. Adsorption was measured according to ASTM C128-01, “standard test method for density, relative density (specific gravity), and absorption of fine aggregate”.

WFS flowable fill’s geotechnical properties determine its serviceability and durability in actual applications. Table 3 presents the tested parameters and used testing specifications. The flowability is a measure of the spreading capacity of fresh flowable fill that is allowed to collapse freely and is an important property to control material’s work consistency. Flowability tests were conducted according to ASTM D6103-97, “standard test method for flow consistency of controlled low strength material (CLSM)”. Bleeding (release of excess water) of flowable fill leads to increased contact of particles and enhances setting of flowable fill, which prompts early strength gains of flowable fill. Bleeding characteristics were evaluated according to ASTM C232-99, “standard test methods for bleeding of concrete”. Flowable fill’s setting is a gradual process and is quantified in time by measuring penetration resistance (PR) of newly-placed flowable fill at intervals. PR was tested according to ASTM C403-99, “standard test method for time of setting of concrete mixtures by penetration resistance”. UC strength tests were performed at day 3, 7, 14, 28, 90 and 180 to monitor material’s strength gains and assist mixture design. UC strength tests were conducted according to ASTM D4832-02, “standard test method for preparation and testing of controlled low strength material (CLSM) test cylinders”.

WFS flowable fill’s leaching properties assess its toxicity and environmental impact. Hydraulic conductivity is a useful property in evaluating contaminant leaching potentials. Hydraulic conductivity of 28-day hardened specimens were determined according to ASTM D2434-00, “standard test method for permeability of granular soils (constant head)”. Two channels may transport contaminants from a WFS flowable fill matrix to surroundings: bleed water released from fresh materials and leachate extracted from hardened fills. These two media were sampled and analyzed with regard to their regulated metallic and nonmetallic contaminants using a toxic characteristics leaching procedure (TCLP) (US EPA, 1992).

Mix proportions and specimen preparation

Final mix proportions adhering to US PennDOT Type A and B flowable fills strength criteria are presented in Table 4. Note that proportions were back-calculated in term of the actual batch yield.

Cement, fly ash, WFS and water, were batch-fed into a power driven revolving concrete mixer. The mixture was blended for approximately 15 minutes until the produced slurry turned into a homogeneous phase and the spreading in flowability tests reached 20 cm. Cylindrical specimens (Ø 10.2×20.4 cm) were prepared by filling fresh materials into plastic molds in accordance with ASTM C192-02, "standard practice for making and curing concrete test specimens in the laboratory". Specimens for setting time tests were prepared by placing fresh slurry into waterproof containers. Cylindrical specimens were kept at 23 ºC and exposed to ambient air for one day, after which the molds were removed and the specimens were placed into a curing chamber (23 ºC, 100% relative humidity) until specimens' testing ages. The steel molds containing flowable fills for hydraulic conductivity tests were placed immediately into the curing chamber after the placements.

Results and discussion

Physical properties of WFS

Fig. 1 shows the gradation curves of 17 WFS samples. According to Unified Soil Classification System (ASTM D2487-06), coefficient of curvature, C_c, ranges from 1.5 to 2.5; coefficient of uniformity, C_u, ranges from 0.9 to 1.5. Samples are classified as poorly graded sands, sometimes with fines. Approximately 90% grains fall between 0.15 mm (5% quantile) and 0.80 mm (95% quantile). The gradation results are consistent with previous investigations (Naik and Singh, 1997a, 1997b; Abichou et al., 2000; Kleven et al., 2000; Naik et al. 2001). The dash lines in Fig. 1 represent the upper and lower limit gradation of conventional fine aggregate (granular sand) specified in ASTM C33-02, “standard specification for concrete aggregates”. WFS was less graded and finer than the fine aggregate. The fineness helps limit mixture segregation and provides a favorable flow of WFS flowable fill in comparison to conventional flowable fill.

Table 5 summarizes test results of WFS sample physical properties. Each value was obtained through a sample test. WFS samples from steel-based facilities (WFS16, WFS17) had GFNs ranging from 49 to 55. WFS samples from iron-based facilities (WFS01 to WFS09, WFS13 and WFS15) had a GFN ranging from 42 to 77. WFS samples from nonferrous facilities (WFS10 to WFS12 and WFS14) had the widest GFN range. The GFNs are nearly the same at the lower ranges for steel, iron and nonferrous WFS. But the upper ranges are greater for nonferrous WFS samples and followed by iron and steel WFS samples. The association of GFN with casting types is possibly due to the variation in casting requirements. Steel castings typically use a relatively coarse grain size to permit gases to rapidly release during the casting processes. Copper/aluminum-based facilities generally use finer grain sand to obtain a refined finish.

Moisture contents vary between 0 to 4.85% and appear to be different for clay-based and organic-based WFS samples. Pure clay-based WFS samples (WFS01, WFS04, WFS08 to WFS10, WFS15 and WFS16) have moisture contents of 1.02% to 4.08%. Less than 1% water content occurred in organic-based samples (0.29% for WFS02 and

0.64% for WFS12). This difference may be related to the varied initial water contents set in the foundry system sands. Clay-based system sands require approximately 10% water content to “activate” bentonite binding, nevertheless 2% to 3% water is needed as a solvent or catalyst to activate organic binders in the organic-based system sands (Winkler and Bol’shakov, 2000). Thus, relative more water remains in clay-based WFS than in organic-based WFS. Ignoring this part of water can result in poor calculation of the entire mix water volume.

Four shapes are recognizable for WFS grains: round, subangular, angular and compound. Fig. 2 depicts grain shapes according to gradation for a representative test, with the round being the predominant shape. It is also shown that round and subangular grains prevail and occupy the middle size segments. Compound and angular grains, at much less mass ratios, are identified for two tail size grains. The predominant grain shapes of all samples are tabulated in Table 5. Round and subangular shapes prevailed grain shapes for the investigated WFS samples. Grain shape is important with respect to flowability, compaction and strength. Round grains provide superior flowability and compaction yet lower strength yield compared to angular grains. Thus, WFS grain shapes enhance flowability of flowable fill mixture.

Two sets of fine content results are presented in Table 5, i.e., particle ratios less than 75 μm by dry sieving and by washing (wet sieving), respectively. The former ranges between 0 to 1.35%, except sample WFS14 (9.21%) which was employed to attain finer finish for nonferrous castings. The latter ranges between 0.34 to 14.75% and is on average 6.74%, consistent with previous investigation results (Abichou et al., 2000). The difference between two sets of fine content ranges suggests that materials less than 75-μm can be separated from larger particles much more efficiently and completely by washing than by vibrating. Interpretations may include more degradation of particles and break-up of compound grains during dispersing and washing than during vibrating. Pure bentonite-based WFS samples, (WFS04, WFS07 to WFS10, and WFS13 to WFS16) contain relatively more fines (on average 7.78%) than organic-based WFS samples (<1.5% for WFS02, WFS12 and WFS17) according to wet sieving results. It is inferred that bentonite occupied the majority of fine contents for bentonite-based WFS. Besides clay contents, fines are also composed of silt and a portion of the very fine sand particles that are dispersed by the wash water, and the remnant chemical additives and binders from the casting processes. Although relative low in amount, the portion of fines, i.e., bentonite, chemical additives and binders, might play a role in cement hydration processes.

The variation in the density (1052 to 1554 kg/m^3), specific gravity (2.38 to 2.72) and absorption (0.38% to 4.15%) measurements may be attributed to the variation in sand mineralogy, particle gradation, grain shapes and fine contents. Good gradation and round shape lead to a compact structure and high density. Lake sand and repetitive molding always result in round grain shapes. A statistical regression test indicates that the higher fine contents, the higher absorption potential (R^2=0.76). The highest absorption (4.15%) is found associated with sample WFS14, which was obtained from a copper/aluminum-based facility. Sample WFS14 also has the highest GFN and fine content among investigated samples as shown in Table 5. Correlation of absorption with fine content and grain size can be interpreted by the law that a finer particle leads to a higher specific surface area, which favors the absorption of water.

Casting processes play an important role in forming the variation of the physical properties of investigated WFS samples as presented in Fig. 1 and Table 5. A variety of casting processes are used in current foundry facilities, featured mainly in the aspects of metal types, refractory material originals, binders, additives, binding systems, mold and core reclamation operations. These factors affect the process of reshaping virgin foundry sand into WFS (Naik and Singh, 1997a; Naik et al., 2001). In addition, different metal casting facilities use varied grain sizes for foundry sands, e.g., finer sands for nonferrous facilities and coarser sands for steel facilities. On the other side, identical casting processes tend to discharge WFS similar in physical properties. Therefore, the division of WFS waste streams according to casting processes may result in a relatively homogeneous material. Otherwise, composite disposals likely adversely increased the variation in WFS physical properties.

Geotechnical properties of WFS flowable fills

Flowability of WFS flowable fill is essentially associated with particle gradation, grain shapes and water contents. Narrow gradation and leading round/subangular shapes facilitate the flow of a fresh WFS flowable fill. Water additions are also favorable to the flowability of flowable fill mixtures, which play mainly as lubricative coatings around grains. Excessive water additions are not desired as they may increase bleedings and volume instability, prolong the setting time and degrade the quality of WFS flowable fill. Water addition processes were uniquely controlled by reaching the spreading diameter threshold value (20 cm) in flowability tests. The amount of water addition in each batch depends on the physical properties of fine aggregate and component proportions in the mixture (Bhat and Lovell, 1997). Since WFS samples are generally finer and have greater specific surface area than conventional fine aggregates, WFS flowable fills not only require relatively more water than conventional flowable fills, but settle out more slowly and tended to retain more water.

Elapsed time and accumulated volume of bleed water are two parameters characterizing bleeding. Fig. 3 shows relationship between bleed volume, elapsed time and the water content of WFS flowable fills. Bleeding of WFS flowable fill normally takes 3-6 hours, with a bleed volume up to 9% of fresh flowable fills. No general inference is indicated about the relationship between bleed volume and elapsed time. Higher water contents of flowable fill do not necessarily lead to a greater bleed volume among tested WFS flowable fills, as the amount of bleed water depends not only on water contents of the materials, but also on component proportions and material properties.

Interpolation was used to estimate the elapsed time corresponding to critical PR values, i.e., 0.34 MPa (50 psi) and 0.69 MPa (100 psi), and the PR values corresponding to elapsed time of 6, 12, 18 and 24 hours. The time to attain 0.34 MPa PR, which is sufficient to support foot traffic and allow further loading without a substantial settlement, is defined as the initial set time. The results are presented in Table 6. It is shown that the initial set of WFS flowable fill starts from 6.7 hours and is on average between 15 to 20 hours. The PR gain from 0.34 MPa to 0.69 MPa requires 2-4 hours. Overall, the PR gains are not uniform. Some flowable fills, i.e., using WFS02, WFS04, WFS06 to WFS09, WFS13 and WFS17, exhibit relatively fast gains of PR, less than 10 hours to reach 0.34 MPa whereas some flowable fills, i.e., using WFS01, WFS03, WFS05, WFS10 to WFS12, WFS14 to WFS16, are relatively slow in early PR gains, over 10 hours or up to 36 hours to reach an initial set after placement. The scattered PR gains are likely attributed to the variation in mix components and proportions. Admixtures or fast-set cement are suggested to expedite PR gains of slow-set WFS flowable fills or to construction works requiring less than 12 hours initial set time. However, Butalia et al. (2004) reminded that flowable fill mixes should be designed to satisfy a set time requirement and then modified without compromising UC strength or excavatability.

Coefficients of permeability are presented in Table 7. It is indicated that interior and exterior permeability coefficients are close or in the same order for a specimen, which means that the seepage through the cylindrical specimen is largely uniform and no abnormal volume of water permeates along the mold internal wall. The average permeability coefficient is typically in the order of 10^{-6} to 10^{-7} cm/sec for investigated WFS flowable fills, and is comparable to the hydraulic conductivity of fine-grained materials, i.e., sandy to silty soils. The largely same level hydraulic conductivity of observed materials also supports findings by Naik et al. (2001) that the effect of foundry sand source on permeability is negligible. Flowable fills using WFS10 and WFS14 have relatively low hydraulic conductivity, in the order of 10^{-9} cm/sec or less. Low hydraulic conductivity WFS can even be used in the construction of seepage cutoffs, dam cores, liners, and landfill covers.

UC strength results of hardened WFS flowable fills at curing ages of 3, 7, 14, 28, 90 and 180 days are presented in Table 8. Among tested specimens, strengths gradually gain throughout the testing periods, i.e., from 0.11-0.28 MPa at day 3, 0.21-1.53 MPa at day 28, to 0.47-9.79 MPa at day 180, largely consistent with the findings in other studies (Naik and Singh, 1997a; Naik et al., 2000; Dingrando et al., 2004). Variation in UC strength gains exists among different materials, which may be associated with varied mix component (WFS) and proportions. At day 28, UC strengths fall within strength requirements (less than 0.86 MPa) of excavatable Type A and B flowable fills specified by US PennDOT (2003), except that 28-day UC strength of WFS14 flowable fill exceeds the strength threshold value. WFS14 flowable fill's cement proportion (15 kg/m^3 in Table 4) is the least among investigated fills. Its fly ash and WFS proportions (Table 4) do not vary significantly from those of other fills, whereas sample WFS14 contains relatively higher amount of fines (14.75% by wet sieving and 9.21% by dry sieving in Table 5) than those of other WFS samples (6.2% and 0.53% on average, respectively). This portion aggregates consist of clays, remnant additives or else which might influence cement hydration processes and thus UC strength gains. Cement proportion of WFS14 flowable fill is suggested to be further reduced to meet strength requirements of excavatable flowable fill, or investigated WFS14 flowable fill serves permanent fill structures. In this investigation, UC strengths continuously gain until the last testing date (day 180) and would possibly continue increasing thereafter, which may disturb the excavatability of fills. In addition to the 28-day UC strength, long-term strength is suggested as a parameter to control excavatability for WFS flowable fills.

The correlations between 28-day UC strength and 12-hour PR or 180-day UC strength are presented in Fig. 4. There is not significant correlation between 12-hour PR and 28-day UC strength among investigated WFS flowable fills. PR of a fresh phase flowable fill is mainly influenced by the frictional strength of the fill which is related to particle gradation, grain shape, settlement and bleeding. UC strength at day 28 is mainly dependent on cement hydration or binding effect. To predict 28-day UC strength using PR in fresh phase is not reliable. Although UC strength still gains after 28 days until 180 days, no general inferences can be made regarding the predicting of long-term strength using 28-day strength as other variables including component proportions are not isolated in the mix design.

The correlation between water-cement (W/C) ratio and 28-day UC strength is presented in Fig. 5. W/C ratios of investigated WFS flowable fills largely range between 4.2 and 12.3, exclusive of isolated observation for WFS14 flowable fill. Scatted results suggest poor correlation between these two parameters. In general, however, W/C ratio is known as an influential parameter in strength gains of cementitious materials. A lower W/C ratio generally results in a higher strength. The discrepancy is possibly attributed to two aspects: the relatively high W/C ratios (4.2 to 12.3) of flowable fills compared to generally 0.4 to 0.7 for concrete, and the varied mix proportions and WFS. In the case of WFS flowable fill, water content is mainly responsible for and determined by the flow requirement of materials, and cement content is generally related to strength requirement of materials. Excavatable flowable fill needs low strength and high flowability. It is thus possible that partial water volume becomes excessive during cement hydration processes and bleeds out or evaporates. As a result, designed W/C ratios do not represent actual W/C ratios, and thus may not clearly correlate with strengths. Dingrando et al. (2004) also found similar insensitive of UC strength of W/C ratio when W/C ratio is greater than 6.5 and interpreted the cause as insufficient cement being present to form a continuous cement matrix. On the other side, variation in mix components and proportions may also affect effects of W/C ratios on strengths. In this investigation, 17 independent WFS samples were incorporated as a major component into flowable fills of varied mix proportions. Factors, e.g., clay and remnant binders contents, fly ash proportions, varied WFS physical properties, may exert an effect on strength gains, which affects the relationship between UC strength and W/C ratio.

Leaching properties of WFS flowable fills

Table 9 presents the contaminant analysis results, i.e., metals and organic compound contents in select WFS flowable fill bleed water samples, and in TCLP leachates of select hardened WFS flowable fills. Corresponding TCLP toxicity threshold values are shown as well. Those observations below detection limits are indicated with sign “<”, followed by the detection limits. The detection limits are referred as the upper boundaries of actual concentrations and compared to threshold values for regulatory compliance.

WFS flowable fill's metallic assessment is important due to foundry sand repetitive exposures to high-temperature melt metals in the casting processes and thus potential accumulation of heavy or toxic metals onto particle surface. The assessment also plays a role in linking WFS flowable fill's metals and WFS metals characterization. The latter is presented in a companion article by Deng and Tikalsky (2006). For the bleed water from fresh WFS flowable fills, regulated metallic elements, i.e., Ag, As, Ba, Cd, Cr, Pb and Se except Hg, are detected and quantified. For the TCLP leachates from hardened WFS flowable fills, As, Ba and Cr are detected and quantified, whereas Ag, Cd, Hg, Pb and Se are not detectable. All metal concentrations, both quantified and unquantifiable, are below US EPA TCLP toxicity criteria. Accordingly, WFS flowable fills investigated in this study do not pose an environmental hazard with regard to metals.

Organic remains may be present in WFS due to the use of organic binders, although most parts of organic binders are burned or shaken away in the casting processes. In Table 9, two organic compounds, acetone and naphthalene, are detected and quantified in both bleed water and TCLP leachates. Concentrations of these constituents are well below US EPA TCLP toxicity criteria. The other organic compounds are not detectable, and their detection limits (upper boundaries) are below corresponding threshold values. Overall, all regulated organic compound concentrations fall within toxicity criteria. Thus, the WFS flowable fills investigated in this study do not pose an environmental hazard with regard to the tested organic compounds.

Recommended mixture formulation

Formulation of WFS flowable fill is generally determined according to the material's fitness to critical engineering behaviors, i.e., UC strength gains and flowability. In investigations, strength requirements of excavatable flowable fills were met by adjusting or revising cement proportions, which was also concluded by Naik and Singh (1997a). Flowability is affected by multiple factors, including fine contents, gradation, grain texture/shape, component proportions and water contents (Crouch et al., 2004; Dingrando et al., 2004). Of these factors, water acts as a lubricator enabling the effects of the other factors on flow and a modulator filling a possible gap between the flow rendered by the other factors and the standard. Since the cement and water proportions were designed on a case-by-case basis and no general inference was concluded in this study, a final quantified formulation for WFS flowable fill is temporarily hard to establish.

Dingrando et al. (2004) recommended a starting formulation according to bentonite contents in WFS components, which recognizes the WFS physical property's effect on mix design. In this study, different WFS flowable fills vary their formulations to fit the specification of an excavatable flowable fill. The formulation variation deserves to represent a formulation range of qualified fills and thus plays as a scouting or starting formulation for new WFS flowable fills. Table 10 summarizes the formulation ranges. Different input components can vary in density, flowability, setting time, UC strength, and other properties of fresh or hardened flowable fills. Alternate formulations may be worked out only if the specification of an excavatable flowable fill is attained.

Concluding remarks

A laboratory test program was conducted to study the workability and suitability of WFS samples from a wide variety of sources as a major component in excavatable flowable fills. The test program was designed to investigate physical properties of WFS, geotechnical and leaching properties of WFS flowable fills. A series of critical parameters were tested and discussed, i.e., gradation, grain shapes, and fines for WFS samples, flowability, hydraulic conductivity, setting time and PR, bleeding, UC strength, contaminants in bleed water and TCLP leachates for WFS flowable fills. The incorporation of these WFS samples into flowable fills were validated from both technical and environmental perspectives. A starting or scouting mixing formulation was suggested, i.e., cement (25 to 94), fly ash (334 to 463), WFS (818 to 1264), and water (291 to 504), in unit kg/m^3.

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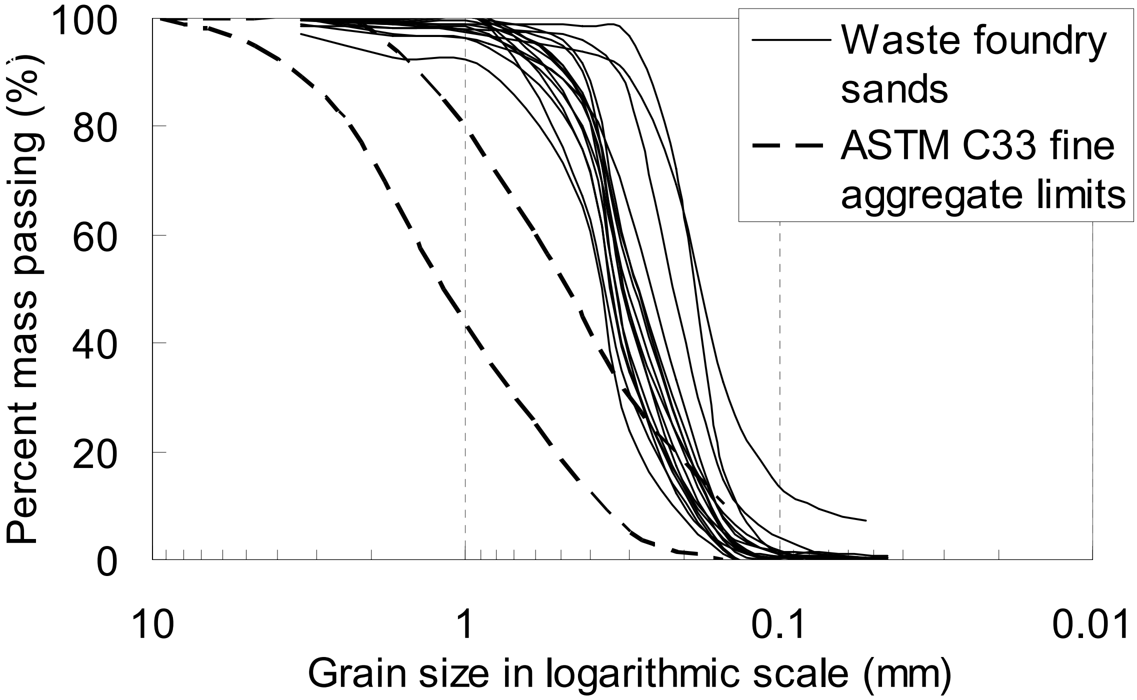
Fig. 1. WFS samples and standard fine aggregate's gradation curves.

Fig. 2. Sample WFS12 grain shapes according to its gradation.

Fig. 3. Correlation between WFS flowable fill's bleeding volume and duration or water proportion.

Fig. 4. Correlation between WFS flowable fill's 28-day UC strength and 12-hour PR or 180-day UC strength.

Fig. 5. Correlation between WFS flowable fill's 28-day UC strength and W/C ratio.



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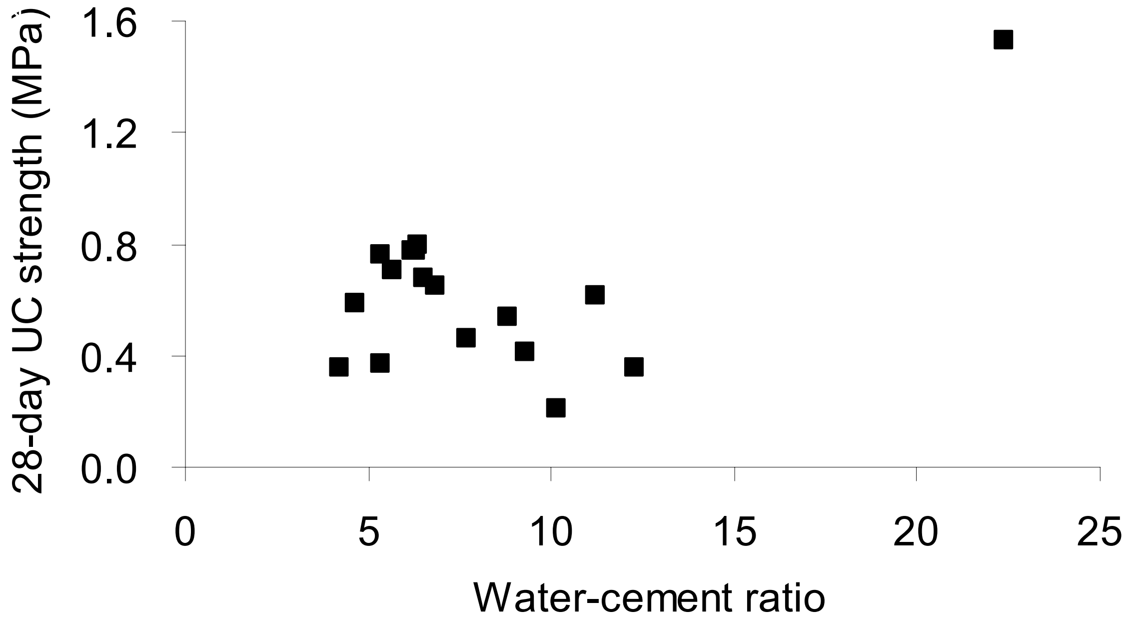

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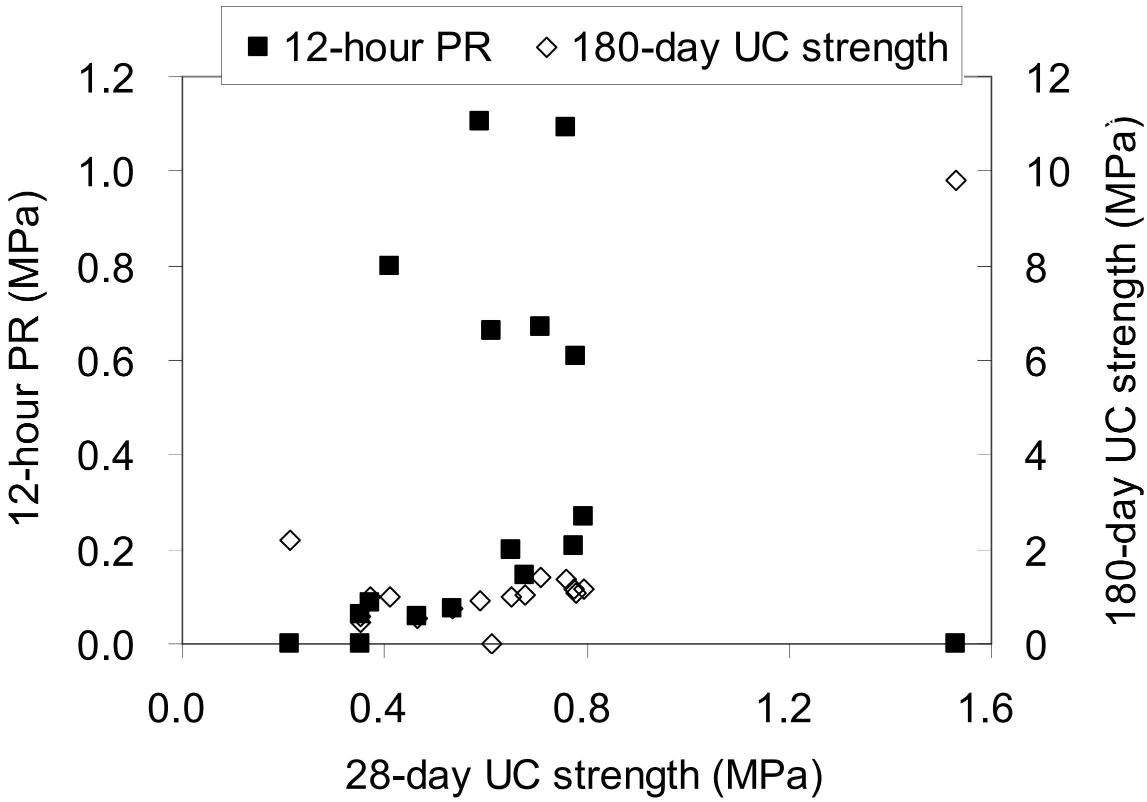

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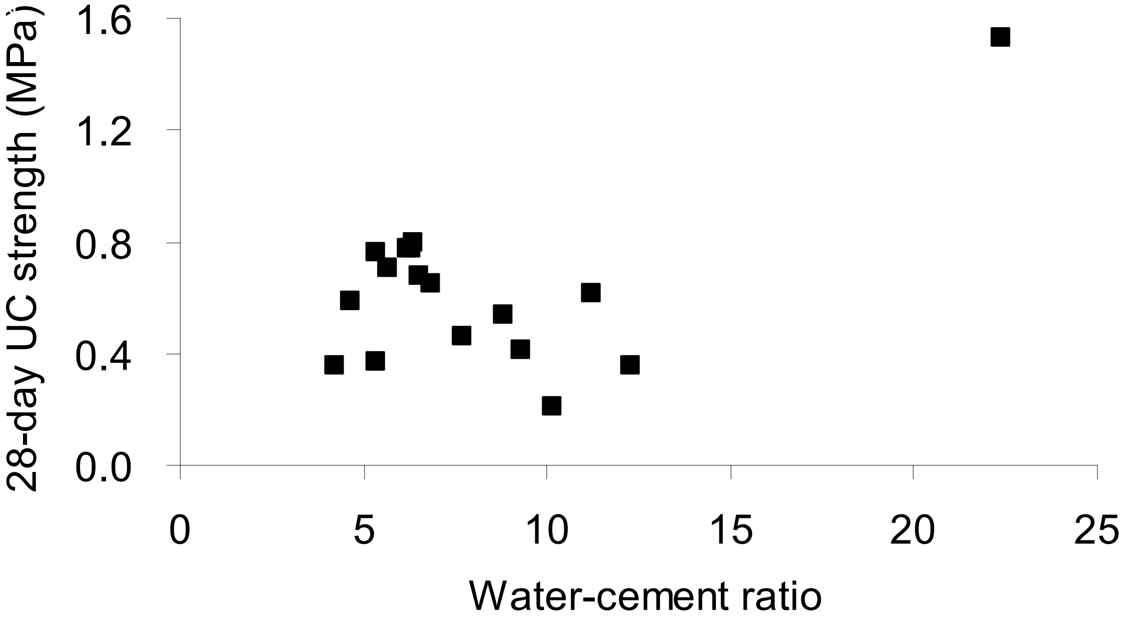

Fig. 5. Correlation between WFS flowable fill's 28-day UC strength and W/C ratio.

Table 1 Casting processes of WFS samples.

Sample ID	Metals cast	Binders	Binding systems
WFS01	Iron	Bentonite and phenolic urethane	Green sand
WFS02	Iron	Furfural alcohol	---
WFS03	Iron	Bentonite and phenolic urethane	Green sand and cold box/shell
WFS04	Iron	Bentonite	Green sand
WFS05	Iron	Bentonite and phenolic urethane	Green sand and shell/cold box/no-bake
WFS06	Iron	Bentonite and sodium silicate	Green sand and sodium silicate
WFS07	Iron	Bentonite	Green sand
WFS08	Iron	Bentonite	Green sand
WFS09	Iron	Bentonite	Green sand
WFS10	Aluminum	Bentonite	Green sand
WFS11	Aluminum	Bentonite and phenolic urethane	Green sand and isocure
WFS12	Aluminum	Phenolic urethane	No-bake
WFS13	Iron	Bentonite	Green sand
WFS14	Copper/aluminum	Bentonite	Green sand
WFS15	Iron	Bentonite	Green sand
WFS16	Steel	Bentonite	Green sand
WFS17	Steel	Sodium silicate	No-bake

Table 2 Physical property tests of WFS samples.

Properties	Testing standards
Particle gradation	AFS 1105
Grain shapes	AFS 1107
Grain fineness number	AFS 1106
Adsorption	ASTM C128

Table 3: Geotechnical and leaching property tests of WFS flowable fills.

Material phases	Properties	Testing specifications
Fresh	Fresh density	ASTM D6023
Fresh	Flowability	ASTM D6103
Fresh	Bleeding characteristics	ASTM C232
Fresh	Setting time and PR	ASTM C403
Fresh	Bleed water contaminants	EPA SW-486
Hardened	Hydraulic conductivity	ASTM D2434
Hardened	UC Strength	ASTM D4832
Hardened	TCLP Toxicity	EPA SW-486

Table 4 Mix proportions (kg/m^3)[a] of WFS flowable fills.

Sample ID	Cement	Fly ash	WFS	Water
WFS01	66	355	970	448
WFS02	73	394	1264	343
WFS03	63	340	876	504
WFS04	70	379	1055	405
WFS05	37	334	972	474
WFS06	64	429	1094	378
WFS07	65	352	1031	428
WFS08	41	370	998	395
WFS09	45	404	1207	320
WFS10	32	463	1212	329
WFS11	66	358	1066	440
WFS12	65	353	1156	359
WFS13	37	394	1242	348
WFS14	15	398	1182	394
WFS15	74	400	818	489
WFS16	94	361	1020	426
WFS17	25	444	1225	291

[a]: component mass per unit volume yield.

Table 5 Physical properties of WFS samples.

Sample ID	GFN	Moisture content (%)	Predominant grain shape	Less than 75 μm (%)		Density as oven-dry (kg/m^3)	Specific gravity	Absorption (%)
				Dry sieving	Wet sieving			
WFS01	50	1.73	SA	0.48	9.57	1289	2.50	3.03
WFS02	49	0.29	RD, SA	0.08	0.34	1382	2.72	0.38
WFS03	52	3.17	SA, RD	0.17	12.07	1285	2.43	2.31
WFS04	77	1.42	SA	1.19	6.99	1423	2.38	2.94
WFS05	61	1.96	SA	0.49	10.60	1370	2.41	1.69
WFS06	42	1.7	CP	0.00	2.19	1095	2.55	1.81
WFS07	60	0	SA, RD	0.66	7.68	1303	2.55	1.56
WFS08	56	2.03	SA, RD	0.50	13.96	1289	2.39	3.35
WFS09	59	1.62	SA, RD	0.52	3.66	1429	2.59	1.09
WFS10	57	3.5	SA, RD	1.35	2.42	1448	2.63	0.52
WFS11	47	4.08	SA, CP	0.08	4.55	1329	2.59	0.86
WFS12	70	0.64	RD, SA	0.37	0.56	1505	2.69	0.79
WFS13	52	0	SA, RD	0.52	0.63	1522	2.64	0.72
WFS14	90	0.14	SA	9.21	13.33	1390	2.48	4.15
WFS15	46	4.08	SA, CP	0.41	14.75	1052	2.38	3.83
WFS16	55	1.02	RD	0.73	9.83	1163	2.52	3.09
WFS17	49	4.85	RD	0.93	1.47	1554	2.64	1.17

AG: angular, RD: round, SA: Subangular, CP: compound.

Table 6 Critical setting times and PR of WFS flowable fills.

Sample ID	Setting time (hour)		PR (MPa)			
	For PR 0.34 MPa	For PR 0.69 MPa	6-hr	12-hr	18-hr	24-hr
WFS01	13.1	17.8	0.02	0.27	0.70	1.16
WFS02	6.7	9.2	0.19	1.10	2.76	4.96
WFS03	25.0	---	0	0.06	0.12	0.33
WFS04	8.7	10.2	---	1.09	2.86	4.47
WFS05	17.1	23.1	---	0.14	0.38	0.71
WFS06	8.4	14.7	0.27	0.56	0.77	0.91
WFS07	9.4	12.8	---	0.61	1.61	2.71
WFS08	8.3	10.2	---	1.02	2.28	3.53
WFS09	9.3	10.4	0.10	1.11	3.56	5.30
WFS10	24.9	31.5	---	0.16	0.17	0.30
WFS11	13.4	16.5	---	0.15	0.81	1.54
WFS12	13.7	16.1	---	0.09	0.98	2.60
WFS13	8.5	9.2	---	2.09	6.27	10.35
WFS14	36.2	44.3	0	0	0	0.11
WFS15	17.8	22.6	0	0.21	0.35	0.83
WFS16	29.8	32.5	0	0	0	0.08
WFS17	8.8	12.2	0.08	0.66	1.39	3.61

“---” results not available.

Table 7 Hydraulic conductivity of WFS flowable fills.

Sample ID	Permeability coefficient (cm/sec)		
	Interior	Exterior	Average
WFS01	---	---	---
WFS02	2.44×10^{-7}	4.41×10^{-6}	2.33×10^{-6}
WFS03	---	---	---
WFS04	1.13×10^{-6}	1.94×10^{-6}	1.54×10^{-6}
WFS05	1.3×10^{-6}	2.01×10^{-6}	1.65×10^{-6}
WFS06	3.4×10^{-6}	3.16×10^{-6}	3.28×10^{-6}
WFS07	3.61×10^{-7}	5.71×10^{-7}	4.66×10^{-7}
WFS08	6.93×10^{-7}	9.81×10^{-7}	8.37×10^{-7}
WFS09	4.28×10^{-6}	5.28×10^{-6}	4.78×10^{-6}
WFS10	1.05×10^{-8}	8.42×10^{-9}	9.47×10^{-9}
WFS11	1.18×10^{-6}	8.46×10^{-7}	1.01×10^{-6}
WFS12	9.04×10^{-7}	3.45×10^{-7}	6.24×10^{-7}
WFS13	1.69×10^{-5}	1.53×10^{-5}	1.61×10^{-5}
WFS14	$<10^{-9}$	$<10^{-9}$	$<10^{-9}$
WFS15	---	---	---
WFS16	8.03×10^{-7}	2.43×10^{-7}	5.23×10^{-7}
WFS17	6.14×10^{-6}	2.66×10^{-6}	4.40×10^{-6}

“---” results not available.

Table 8 UC strengths of WFS flowable fills.

Sample ID	UC strength (MPa)					
	3-day	7-day	14-day	28-day	90-day	180-day
WFS01	0.26	0.29	0.49	0.80	1.07	1.17
WFS02	0.26	0.29	0.41	0.59	0.59	0.90
WFS03	0.16	0.19	0.31	0.46	0.47	0.54
WFS04	0.28	0.36	0.47	0.76	0.98	1.37
WFS05	0.14	0.18	0.25	0.35	0.42	0.47
WFS06	0.11	0.20	0.38	0.71	1.15	1.41
WFS07	0.25	0.25	0.50	0.78	1.04	1.07
WFS08	0.22	0.31	0.42	0.54	0.70	0.77
WFS09	0.23	0.28	0.42	0.65	0.92	1.01
WFS10	---	0.06	0.05	0.21	2.25	2.21
WFS11	0.18	0.27	0.41	0.68	1.09	1.05
WFS12	0.15	0.19	0.29	0.37	0.84	0.99
WFS13	0.23	0.24	0.30	0.41	0.67	0.98
WFS14	---	---	---	1.53	6.05	9.79
WFS15	0.15	0.24	0.42	0.78	0.99	1.14
WFS16	0.18	0.24	0.32	0.35	0.46	0.57
WFS17	0.29	0.56	0.50	0.61	0.59	---

“---” results not available.

Table 9 Bleed water contaminants and TCLP results of WFS flowable fills.

	Bleed water (µg/kg)				TCLP analyses (µg/kg)				US EPA TCLP
Constituents	WFS02	WFS12	WFS13	WFS16	WFS02	WFS12	WFS13	WFS16	criteria (µg/kg)
Arsenic	73.3	18.3	31.4	378	57.2	<50	<500	<50	5000
Barium	620	505	278	289	78.4	291	338	<10	100000
Cadmium	6.4	6.4	7.7	10.2	<10	<10	<10	<10	1000
Chromium	75.8	48.5	189	681	25	60.9	72.2	<10	5000
Lead	26.7	23.1	13.7	93.6	<30	<30	<30	<30	5000
Mercury	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2	200
Selenium	100	31.7	34	26.9	<50	<50	<50	<50	1000
Silver	.6	<.3	<.3	2	<50	<50	<50	<50	5000
Acetone	---	41	56	1540	86	86	100	115	---
Benzene	---	<5	<5	<5	<25	<25	<25	<25	500
Carbon tetrachloride	---	<5	<5	<5	<25	<25	<25	<25	500
Chlorobenzene	---	<5	<5	<5	<25	<25	<25	<25	100000
Chloroform	---	<5	<5	<5	<25	<25	<25	<25	6000
1,4-Dichlorobenzene	---	<5	<5	<5	<25	<25	<25	<25	7500
1,2-Dichloroethane	---	<5	<5	<5	<25	<25	<25	<25	500
1,1-Dichloroethene	---	<5	<5	<5	<25	<25	<25	<25	700
Ethyl benzene	---	<5	<5	<5	<25	<25	<25	<25	
Methyl ethyl ketone	---	<10	<10	<10	<50	<50	<50	<50	200000
Methylene chloride	---	<5	<5	<5	<25	<25	<25	<25	---
Naphthalene	---	619	180	115	<25	616	527	<25	---
Styrene	---	<5	<5	<5	<25	<25	<25	<25	---
Tetrachloroethene	---	<5	<5	<5	<25	<25	<25	<25	700
Toluene	---	<5	<5	<5	<25	<25	<25	<25	---
1,1,1-Trichloroethane	---	<5	<5	<5	<25	<25	<25	<25	---
Trichloroethene	---	<5	<5	<5	<25	<25	<25	<25	500
Vinyl chloride	---	<10	<10	<10	<50	<50	<50	<50	200
M, P-xylene	---	<5	<5	<5	<25	<25	<25	<25	---
Xylene-total	---	<10	<10	<10	<25	<25	<25	<25	---

"---" results not available. "<5" constituent nondetectable, in which "5" represents detection limit.

Table 10 Recommended starting mix formulations (kg/m^3)[a] of WFS flowable fills.

Ranges	Cement	Fly ash	WFS	Water
Lower range	25	334	818	291
Upper range	94	463	1264	504
Average	57	383	1075	399

[a]: component mass per unit volume yield.