



Investigation of Alternative Ways for Recycling Waste Foundry Sand: An Extensive Review to Present Benefits

Journal:	<i>Canadian Journal of Civil Engineering</i>
Manuscript ID	cjce-2017-0183.R1
Manuscript Type:	Review
Date Submitted by the Author:	13-Nov-2017
Complete List of Authors:	Gedik, Abdul; ITU, Transportation Engineering Lav, Abdullah; lav@itu.edu.tr, Dept. of Civil Engineering; Istanbul Technical University, Lav, Musaffa; Istanbul Technical University, Civil engineering
Is the invited manuscript for consideration in a Special Issue? :	N/A
Keyword:	Recycling, Waste foundry sand, Metal casting, Bentonite

SCHOLARONE™
Manuscripts

Investigation of Alternative Ways for Recycling Waste Foundry Sand: An Extensive Review to Present Benefits

Abdulgazi Gedik^{1*}, Abdullah Hilmi Lav², Musaffa Aysen Lav³

¹Ph.D., Graduate of Transportation Engineering, Faculty of Civil Engineering, Istanbul Technical University, Istanbul 34469, TURKEY *Corresponding author, Tel.: +90 212 285 65 85, Fax: +90 212 285 65 87 e-mail: gedikab@hotmail.com

²Ph.D., Professor of Civil Engineering, Faculty of Civil Engineering, Istanbul Technical University, Istanbul 34469, TURKEY, Tel.: +90 212 285 65 85, Fax: +90 212 285 65 87 e-mail: lav@itu.edu.tr

³Ph.D., Professor of Civil Engineering, Faculty of Civil Engineering, Istanbul Technical University, Istanbul 34469, TURKEY, Tel.: +90 212 285 65 82, Fax: +90 212 285 65 87 e-mail: aysen.lav@itu.edu.tr

A B S T R A C T

Foundry sand, an indispensable component of the metal casting process, is discarded after a number of metal casting operations. Since virgin sand is required for the new processes, and the spent foundry sand is treated as waste, a huge amount of discarded sand is either stockpiled or dumped into landfills. This results in a wide scale consumption of natural resources despite the fact that this "waste" can be recycled as a viable resource in various engineering processes. To this end, this study represents a detailed investigation into the possible uses for waste foundry sand. Obtained results concluded that this material can best be utilized in highway and hydraulic barrier construction, as well as low strength concrete production. Thus, the recycling of waste foundry sand results in the conservation and saving of natural and financial resources.

Keywords: Recycling; Waste foundry sand; Metal casting; Bentonite

Introduction

A foundry is a manufacturing plant that produces metal castings by pouring molten metal into pre-shaped molds. This process requires the use of foundry sand, a kind of high quality size-specific silica sand. Generally speaking, approximately one ton of foundry sand is needed to produce one ton of metal casting (Collins and Ciesielski 1994). Sand's resistance to high pressure and heat of the molten metal, its easily availability, and its low cost rank among the main reasons why this kind of material is

utilized in the foundry process. All such sands are not identical, however, and they are classified based on their types of binder systems. The first and most common type (90%) is clay-bonded sand, namely green sand, while the second is termed chemically-bonded sand. Green sand is composed of high quality silica sand (85-95%), bentonite clay (4-10%) as its binder, carbonaceous additive (2-10%) to improve the casting surface finish, and water (2-5%). Chemically bonded sand consists of 93-99% silica and 1-3% chemical binder by weight (Beeley 2001; Clegg 1991). The binder provides cohesion to the silica sand so as to retain the shape of the mold during the casting process.

Following several utilizations, the heat degradation incurred from repeated pouring ultimately renders the foundry sand particles too fine for further use. At this stage, the "spent" foundry sand must be replaced with virgin sand (CWC 1995). This replacement results in a continuous outflow of molding sands from the foundry process; therefore, the total waste production in a cast iron foundry is about one ton of waste (of which the 50% b.w. is comprised of molding sands) for one ton of casts (Zanetti and Godio 2006).

The annual world's casting production of several countries is given in Table 1. These figures allow researchers to estimate the current situation and amount of waste foundry sand (Annual Census of World Casting Production 1991, 2003, 2004, 2005).

Table 1.

However, instead of replacing the spent sand with virgin sand, the recovery of large quantities of spent foundry sand is possible by using a procedure known as reclamation. Green sand reclamation involves the removal of the clay and carbonaceous material bound to the silica sand grains and the retention of the particle size distribution of the original silica sand grains. Cruz et al. (2009) completed an experimental study on green sand reclamation using a fluidized bed with an attrition nozzle. They demonstrated that the approximate cost of the required energy for reclamation of spent sand was \$23 per ton, excepting additional expenses such as equipment, installation and maintenance, and labor. The researchers may compare that figure to those of other sources who reveal that the price of new silica sand may range from \$40 to \$140 per ton (Highway Research Center, U.S. Department of

Transportation: Federal Highway Administration 2006). In the light of Cruz et al.'s (2009) analysis, attrition may be an economically feasible method for recovery of spent foundry sand. However, they indicated that there is currently no industrial scale equipment that reclaims green sand using an attrition nozzle on spent sand, and that there remains considerable doubt about the ultimate quality of reclaimed spent sand (Cruz et al. 2009).

Zanetti and Godio (2006) also presented their research into the recovery of foundry sands and iron fractions from an industrial waste landfill. They tried to recover this by-product in three ways: (i) thermal process, which carries the risk of strong environmental impact and costs about €30-40 per ton. (ii) wet mechanical treatment, which involves a noticeable sludge production and costs about €20-30 per ton. (iii) dry mechanical process, which – to comply with the core making operations – necessitates a unique study for each plant of the organic additives mixture and costs €10 per ton. They also concluded that the European price of virgin silica sand nearly equaled the price of recovery of foundry sand. For instance, in Italy the price is about €40 per ton while, i.e. in Belgium and Netherlands the same product is sold at about €10 per ton (Zanetti and Godio 2006). Therefore, many foundries are reluctant to reclaim spent foundry sand and instead prefer to replace it with virgin sand and discard large quantities of this spent foundry sand, namely waste foundry sand (WFS).

There are currently over 3000 foundries in the United States generating 10 million tons of WFS per year (Siddique 2007). In Europe, the total amount of WFS is approximately 12 million tons per year (Abichou et al. 2004). The vast majority of this WFS (90%) is being dumped into landfills, even though this material has the kind of properties that make it an excellent choice in various engineering applications. Additionally, virgin sand stockpiles in many states and metropolitans are almost exhausted. Hence, many foundries have to deal with such serious problems as the need to locate new areas, to comply with a host of environmental regulations, and to compensate for long hauling distances; for instance, in Istanbul, the largest city of Turkey, transportation and dumping costs of WFS can climb as high as \$15/m³. Add to this the fact that vast amounts of natural virgin materials are

being utilized across the face of the globe in such kinds of applications as highway construction, structural fill, concrete, etc. For example, in Finland alone, over 50 million tons of natural mineral aggregate are being used each year for earth and road construction (Mroueh and Wahlström 2002). Hence, the depletion of materials such as natural sand and gravel in some of the world's most populated areas serves to increase transport distances, thereby driving up costs and increasing the need for by-products like WFS as substitute materials. WFS recycling as a substitute material supports not only the strategic goals of current environmental legislation, but also provides remarkable benefits such as the reasonable conservation of natural resources and a reduction of landfill disposal.

As mentioned above, almost all WFS (90%) is being land-filled, with only the remaining ten percent utilized in various applications. Among the most probable reasons for this low utilization rate it can be counted: (i) WFS can be hazardous to environment, (ii) many engineers are not aware of the quality and index properties of WFS, and (iii) some official associations are reluctant to use this by-product as a substitute material in various applications. Despite this, WFS has been successfully utilized in embankments and/or structural fills, road base and/or sub-base, hot mix asphalt (HMA), flowable fills, soil and/or horticultural, cement and concrete products, traction control, and other applications respectively by volume (U.S. Department of Transportation, Federal Highway Administration 2007).

Before beginning a discussion of the studies related to these applications, it is required to first examine the environmental factors relative to WFS and then its technical properties.

Environmental Effects of WFS

In today's world, many governments – particularly those generally referred to as "developed" – tend to be sensitive to their environments and have developed relative laws and regulations. Most of these regulations demand that by-products must be proven to be both environmentally friendly and technically suitable before they can be utilized. In other words, these materials must be only minimally polluting, or their pollutants must be bound to the material to prevent or their migration to the environment must be kept at minimum levels (Mroueh and Wahlström 2002).

Prior to the casting process, foundry sand is mostly accepted as clean; however, once it has been used in production, it may become hazardous due to the inclusion of heavy metals and leachable contaminants (U.S. Department of Transportation, Federal Highway Administration 2007).

Many past researchers have focused their investigations on the environmental properties of WFS. These studies have demonstrated that WFS does not cause groundwater or surface water contaminations as the measured concentrations were significantly lower than the U.S. Environmental Protection Agency (EPA) maximum concentration limits (Ham et al. 1981; Lovejoy et al. 1996; Naik et al. 2001).

Moreover, according to the experiments conducted by Freber (1996), the concentrations of metals in groundwater underlying highway embankments are comparable with those encountered in the natural environment, i.e., embankments constructed with natural materials. And even though Lee and Benson (2002) and Coz et al. (2004) found that the concentrations of some metals such as zinc, lead, chromium, and iron leaching from WFS may exceed U.S. EPA limits, they also determined that there was only a ten percent – tolerable range – difference between the measured and EPA limit values.

Guney et al. (2006) evaluated the environmental behavior of WFS amended with lime and cement. They claimed that water passing through WFS or WFS-based mixtures did not become contaminated with metallic compounds, due to fact that the measured concentrations were apparently lower than the U.S. EPA limits. In other words, if utilized and if there is contact between the WFS and water that has been discharged directly to the environment (e.g., drainage through asphalt pavement), the quality of the water will not be affected by any metals leached from the WFS or WFS-based mixtures.

Technical Properties of WFS

In order to understand in which applications WFS can be a supplementary material its physical, chemical and mechanical characteristics are provided in Tables 2, 3 and 4 respectively. The durability designating the ability to survive, sustain and perform at permissible levels ranks as one of the most

desired features of a highway. When used as an attribute of road material, durability is defined as the degree to which road material preserves its properties under changing circumstances, particularly weathering. Due to its both lower micro-deval abrasion loss and magnesium sulfate soundness loss value, WFS is expected to have favorable durability characteristics as a highway material. Furthermore, its other features such as friction angle (the angle of shearing resistance), California Bearing Ratio, density, moisture, and plastic index, which are comparable to those of conventional sands, reconfirm this assumption.

Table 2.

Table 3.

Table 4.

Owing to the presence of both clay lumps and friable particles, WFS has a relatively low hydraulic conductivity, underlining the fact that it can be considered a promising material in hydraulic barrier construction.

Consisting of almost 90 percent silica, WFS tends to be hydrophilic and therefore attracts water to its surface. When used in hot mix asphalt, this property can cause an increase in moisture-dependent damage, resulting in stripping of the bitumen coating surrounding the aggregate gains, loss of fine aggregate and detrimental pavement deformations. This phenomenon reveals that only a limited amount of WFS can be used as a supplement for fine aggregate in bituminous mixture.

Potential Areas for Recycling of WFS

WFS in Highway Construction

During both the construction of pavement layers and service life of the pavement, soft sub-grades – particularly fine-grained soils – have always constituted a major problem under repeated traffic loading. There are currently several methods used to strengthen these kinds of sub-grades including its stabilization with chemical agents or by combining two or three different graded soils. Another commonly used method involves replacing these weak sub-grades with a layer of selected granular material (mostly with conventional crushed rock). However, due to the high costs of such materials,

searches for alternative materials are on-going. To this end, Tanyu et al. (2004) investigated four alternative materials (grade 2 gravel, foundry slag, bottom ash and WFS) to compare their equivalency with crushed rock in terms of cumulative total deflection for a pavement. They indicated that – neglecting other issues such as drainage and weathering – the equivalent thickness of alternative materials obtained when their total deflections were equal to that of conventional crushed rock under the same 1000 cycle load. They measured and compared the total deflection results with both an in-laboratory large-scale model experiment (LSME) and with an in-field rolling wheel deflectometer (RWD). LSMEs were performed on each of the working platforms of alternative materials in order to create a relationship between total deflection and working platform thickness for a typical construction loading (1000 trips of a loaded four-axle dump truck). Among the obtained results, the WFS results are shown here in Figure 1 and Table 5.

Fig. 1.

Table 5.

As can be seen from the table, the lowest total deflection of WFS was at its optimum water content (16%) and the highest total deflection was 7% wet of optimum water content (23%). The total deflection of foundry sand compacted at dry of optimum water content (12%) was larger than that of compacted of optimum water content (16%). Thus, we may conclude that the total deflection decreases as the layer thickens.

In order to determine the equivalent working platform thickness for alternative materials, a power function was generated between total deflection (δ) and working platform thickness (h). This equation is as follows;

$$h = \alpha * \delta^\beta \quad (1)$$

where; β and α are fitting parameters. Their WFS values are given in Table 5. We can derive this equation to find equivalent thickness of WFS depending on the thickness of crushed rock as follows;

$$h_{WFS} = \exp \left[\frac{\beta_{WFS}}{\beta_{CR}} * \ln \left(\frac{h_{CR}}{\alpha_{CR}} \right) + \ln \alpha_{WFS} \right] \quad (2)$$

where;

h_{WFS} : equivalent thickness of the alternative material (WFS),

h_{CR} : thickness of crushed rock,

α_{WFS} and β_{WFS} : parameters in Equation 2 for the alternative material (WFS) and

α_{CR} and β_{CR} : parameters in Equation 2 for crushed rock

Using this equation, the thickness of each alternative material was calculated in lieu of a 0.4-m-thick working platform of crushed rock which limited total deflection to 25 mm. The equivalent thicknesses of alternative working platforms were calculated as 0.30 m, 0.45 m, 0.96 m, and 2.5 m for WFS, grade 2 gravel, bottom ash and foundry slag respectively. The equivalent thickness obtained for WFS is very promising since its value is lower than that of crushed rock.

In conclusion, it is clear that among these three by-products (foundry slag, bottom ash, and WFS) due to its total deflection under repeated traffic loads, WFS ranks as an especially favorable material which may be used to replace crushed rock. Additionally, the working platforms constructed with WFS are not thicker in volume than that of crushed rock. This means that WFS can be considered as an alternative material for highway construction provided that other issues such as drainage and etc. are neglected (Tanyu et al. 2004).

In their investigation of the suitability of WFS as a highway base and sub-base material Kleven et al. (2000) conducted a study on 13 different types of WFS and one base sand sample. To make their comparisons these researchers accepted the highway base and sub-base material by WisDOT (Wisconsin Department of Transportation) as their reference materials. As the basis of their study, they performed the California bearing ratio (CBR), unconfined compressive strength (q_u), and resilient modulus (M_R) tests on the samples.

The first part of the study consisted of a determination of the pertinent engineering properties of WFS so as to create empirical correlations relating engineering properties of WFS to index properties. In the second part, three water contents (dry of optimum, optimum, and wet of optimum water content) and two compaction efforts (standard and modified effort) were investigated to understand how they

affect the engineering properties of WFS.

Their test results showed that WFS can be classified as SP (poorly graded sand), SM (silty sand), or SP-SM according to USCS (unified soil classification system) and A-2-4 or A-3 according to AASHTO. WFS samples compacted with standard effort at optimum water content had CBR values ranging from 4 to 40 and averaged 20. However, these values increased approximately 970 percent when the samples were compacted with modified effort. The swell values of all soaked WFS samples were lower than the other samples. WFS samples compacted at optimum water content with standard effort had q_u values ranging from 71 to 190 kPa. M_R of the WFS samples was similar to that of the reference sub-base material but lower than the reference base material. The study of the impact of compaction/water content showed that dry of optimum at greater compaction had minimal effect on M_R , but that M_R decreased by >50 percent when the WFS samples were compacted at wet of optimum water content.

They concluded that since WFS had favorable M_R , q_u , CBR, and other engineering properties when compared with the typical granular sub-base, it may serve as an economic alternative sub-base material in cases of compaction at dry of optimum or optimum water content with higher compaction (Kleven et al. 2000).

Guney et al. (2006) investigated the suitability of amended WFS as a highway sub-base material. They prepared the WFS specimens with cement, lime, and crushed rock. The study included q_u and CBR tests, as well as scanning electron microscopy (SEM) analyses to investigate the effect of cement and lime addition, curing time, molding water content, compaction effort, and mixture gradation. Furthermore winter conditions impacts were observed by conducting hydraulic conductivity and unconfined compression tests on the WFS specimens after freeze – thaw cycles.

Their results proved that the strength of WFS – based mixtures (q_u) is strongly dependent on compaction effort and water content, since favorable results were obtained from samples compacted with higher compactive effort at dry of optimum or optimum water content. They also demonstrated that both lime and cement had a considerable effect on CBR and q_u values of the WFS samples. Their

WFS samples also achieved a greater resistance to winter conditions than had that of the Turkish Highway Administration's two reference highway sub-base materials. For CBR and M_R values, required layer thicknesses were calculated under equivalent single-axle loads (ESALs or W_{18}) of 5 million (Case I) and 50 million (Case II). In both cases, the required sub-base had less thickness when WFS was utilized in lieu of reference materials. They concluded that the WFS satisfied the geomechanical limits and could be safely used as an economic alternative material in highway sub-base (Guney et al. 2006).

Mast and Fox (1998) conducted a full-scale field demonstration project to monitor the performance of WFS as a highway embankment material. Their project was primarily based on determining the geotechnical performance of WFS in terms of deformation, strength, hydraulic conductivity and simplicity of construction. In other words, the goals of this project were to investigate the vertical and lateral deformation of the WFS embankment, in-situ hydraulic conductivity of the WFS, accuracy of field compaction testing methods in WFS, total stress on the embankment foundation, changes in pore pressures in foundation soils during construction, and the post-construction in-situ penetration resistance of the WFS when it was used as a highway embankment. To this end a 275-m length embankment was constructed in three sections: the first one built with clay borrow, the second one built with WFS, and the last one built with natural sand. This is illustrated in Figure 2.

Fig. 2.

WFS section performance is compared to that of the clay borrow and natural sand sections of the embankment. As shown in Figure 3a and 3b, inclinometers and piezometers were used to carry out an in-situ measurement of vertical and horizontal displacement and hydraulic conductivity.

Fig. 3a.

Fig. 3b.

The test results demonstrated that the geotechnical performance of the WFS was as favorable as that of clean, natural sand. Moreover, small internal deformations and a high standard penetration resistance

were also observed. They also determined that it was the amount of fine materials in WFS that most affected its strength, hydraulic conductivity, and compaction characteristics as a highway embankment. Laboratory and field tests indicated the hydraulic conductivity for compacted WFS ranged from 1×10^{-8} to 7×10^{-7} m/s. This result is very close to that of previous studies. From a geotechnical perspective, they concluded that the results demonstrate WFS can be successfully used as an embankment fill material for full-scale highway projects (Mast and Fox 1998).

Yazoghli-Marzouk et al. (2014) assessed WFS as a road material from an environmental standpoint. By means of evaluating its leaching behavior via experimental site monitoring they demonstrated that WFS could be an environmentally-friendly material in road construction.

WFS in Hot Mix Asphalt (HMA)

A few studies have also been conducted on the utilization of WFS as a substitute for the fine aggregate in HMA. Abichou et al. (1999) determined that the premier factor influencing the utilization of WFS in HMA was the amount of the fine particles existing in WFS. They indicated that the fineness of WFS had a negative effect on HMA properties. In other words, the basic properties of the HMA samples that included WFS began to dissipate in parallel with the additions of amounts of WFS. This was especially true for stability properties.

Javed et al. (1994) conducted similar experiments on asphalt concrete samples containing WFS. They found that an amount up to 15% was the maximum amount of WFS that could be allowed to replace conventional sand content in asphalt concrete. However, in the light of their experiments on samples having 0, 4, 7, 10, 14, 17 and 20% replacement of fine aggregate with WFS, Bakis et al. (2006) suggested that using WFS as a partial replacement for fine aggregate in asphalt concrete should be limited to a maximum of about 10% in practical applications. They made this determination based on the fact (i) that, as shown in Figure 4, flow decreased parallel to the increase in the percentage of added WFS (ii) as the percentage of WFS added to the asphalt cement increased from 0 to 20% and the Marshall stability value decreased from 12.1 to 9.7 kN. However, when the WFS content was limited to a maximum of 10% of the whole aggregate weight, the Marshall stability value was 10.9 kN. which

is a fairly good result; *(iii)* similarly the indirect tensile strengths of the asphalt cement samples displayed an almost linear decrease as the percentage of WFS material was increased, resulting in values of 13.9 kPa with 0% WFS, 11.8 kPa for 10% WFS and 9.4 kPa with 20% WFS added. *(iv)* it is well-known that the measured density value of asphalt cement concrete is 2.4 g/cm^3 . However, they measured this value as 2.28 g/cm^3 for asphalt cement concrete sample including 20% WFS. Hence, it is clear that the density of the mixture decreases as the percentage of WFS in the asphalt cement concrete increases as shown in Figure 4.

Fig. 4.

In the same research, they also showed that inclusion of WFS into HMA did not cause any damage to the environment (Bakis et al. 2006).

WFS in Concrete

Khatib and Ellis (2001) investigated concrete samples containing three types of foundry sands as a partial replacement of fine aggregate: white fine sand without the addition of clay and coal; foundry sand before casting process (virgin); and foundry sand after casting process (WFS). In order to determine the optimum amount of these materials, the standard sand was partially replaced by 0%, 25%, 50%, 75%, and 100%. Their results indicated that *(i)* the strength of concrete reduced as the amount of replaced sand increased; *(ii)* concrete samples containing white sand had similar strength to those including WFS at all replacement levels; *(iii)* concrete with high amounts of virgin sand had lower strength compared with concrete incorporating white sand or WFS; and *(iv)* increase in strength was not observed at low replacement levels (less than 50%). The tests on shrinkage up to the age of 60 days were also performed, and according to the results, they indicated that *(i)* length change of concrete increased as the replacement amount of standard sand with the three types of sand increased; *(ii)* WFS based concrete had higher drying shrinkage values; however, white sand based concrete had lower values. *(iii)* expansion was mostly lower in white sand based concrete compared with the other two types (virgin and WFS) at a low sand replacement level of 25% (Khatib and Ellis 2001).

Another research was conducted by Siddique et al. (2009) on concrete samples containing three

different percentages of WFS (10%, 20%, and 30%) substituted for the fine aggregate. They explained that; (i) as seen in Figure 5, an increase in compressive strength was observed due to the fact that WFS is finer than conventional sand. Additionally, it is clear in Figure 6 that higher splitting-tensile strength was observed due to silica content present in the WFS. Likewise, flexural strength, and modulus of elasticity of WFS based concrete increased in line with the increase in foundry sand content as shown in Figure 7 and 8; (ii) compressive strength, splitting-tensile strength, flexural strength, and modulus of elasticity of concrete mixtures increased with age for all the WFS contents as seen in Figure 5, 6, 7, and 8. (iii) increase in compressive strength varied between 8% and 19% depending upon WFS percentage and testing age, whereas it was between 6.5% and 14.5% for splitting-tensile strength, 7% and 12% for flexural strength, and 5% and 12% for modulus of elasticity.

Fig. 5.

Fig. 6.

Fig. 7.

Fig. 8.

According to their obtained results, they concluded that WFS could be promisingly utilized to provide a-high quality concrete (Siddique et al. 2009).

In addition to various strength-related tests, Manoharan et al. (2017) evaluated micro-structural properties of concrete with WFS in a recent study. After investigating the presence of various compounds and micro cracks by image-analysis, the authors suggested that WFS up to 20 wt% could be proposed to be recycled as an alternative material for concrete industry.

In an environmentally-focused study, Siddique et al. (2018) showed that the use of WFS as replacement of conventional sand did not only lead to a decline in the cost of concrete, but also to a considerable reduction in CO₂ emissions. In another similar study, leachability characteristics of the concrete specimens with WFS at different pH conditions representing variant natural cases revealed that WFS could be utilized in the production of concrete with no hazardous effects in terms of the topic's environmental aspects (Basar and Aksoy 2012).

WFS in Controlled Low Strength Material (CLSM)

CLSM – having a maximum compressive strength of 8.3 MPa at 28 days – is defined as a self-compacted, cementitious material utilized as backfill in place of compacted fill. This material is designated by a number of different names: flowable fill, unshrinkable fill, controlled density fill, flowable mortar, etc. (ACI Committee 229 1994). Typically, it is composed of sand, cement, fly ash, and water.

Siddique (2009) noticed innumerate advantages of this material: its generation from by-products (especially from WFS), its fast manufacture, self-compaction, simple excavation, and its utilization in confined spaces. Kennedy and Linne (1987) specified that WFS is a convenient material for CLSM production due to its performance, lower cost, and availability. In order to validate the incorporation of WFS into CSLM from an environmental perspective material leaching analyses are required. To this end, Deng and Tikalsky (2008) conducted extensive experiments and showed that the toxicity of CLSM specimens with WFS was below regulated criteria without posing any environmental hazard with regard to toxic metals. Additionally, the U.S. EPA accepted ferrous WFS as a suitable CLSM material (Environmental Protection Agency 1998). To date, several studies have been conducted on the issue of replacing WFS with natural fine aggregate. Tikalsky et al. (1998) investigated both green and chemically bonded WFS in CLSM and compared results with CLSM containing uniformly graded crushed limestone sand. According to their results, CLSM containing WFS gave similar or better results in terms of strength than CLSM containing crushed limestone sand. WFS supported strength retention from exceeding the desired upper limit of 700 kPa. However, when compared to each other, chemically bonded WFS performed better than green WFS in CLSM on the issue of fluidity (Tikalsky et al. 2000).

Since strength and flow rank as the two most important CLSM parameters, those factors affecting strength and flow should be investigated very carefully and methods to prevent flow loss need to be determined. It was to this end that Dingrando et al. (2004) investigated the effects of WFS and its bentonite presence on flow and compressive strength characteristics of CLSM. Their results

indicated that bentonite content does not play a major role on the compressive strength of CLSM containing WFS; however, it does have an indirect effect in that WFS with higher bentonite presence requires more water to flow, which affects strength. Compressive strength of CLSM made of WFS mostly depends on water cement ratio (W/C) and for $W/C < 6.5$, CLSM generally has excessive compressive strength, whereas a suitable value is obtained with $W/C > 0.65$. During their study, the researchers also analyzed the factors affecting flow loss. They determined that the presence of cementitious fly ash represented the most important factor affecting flow loss in CLSM. CLSM with cementitious fly ash showed much greater rates of flow loss. Thus, flow loss can be reduced appreciably by introducing WFS whose bentonite is at least 6% so that fly ash fines do not have to be added to CLSM. Their conclusions suggested a mixture calculation for CLSM as shown in Table 6 (Dingrando et al. 2004).

Table 6.

Therefore, in the light of these previous studies, it is clear to say that WFS can be utilized in lieu of sand in CSLM without any hesitation.

WFS as Hydraulic Barrier

Geotechnical applications – mainly pavements and high embankments – are susceptible to water. Currently, geomaterials such as geomembranes are used to protect these structures against the detrimental effects of water. These materials, however, remain costly. On the other hand, WFS, a by-product of the molding industry and one that is being ignored and stockpiled has the kinds of fine components that allow its utilizations as hydraulic barriers. Abichou et al. (2004) conducted a project in which they constructed three test pads to investigate the hydraulic conductivity of WFS. During the project, a network model based on the packing of equal size spheres (0.2mm) was developed to estimate the hydraulic conductivity of WFS. This model, which is illustrated in Figure 9, provided; (i) generating packings of equal-sized spheres to simulate sand grains, (ii) extracting networks of capillary tubes representing the void space in the packing of spheres, (iii) calculating the hydraulic conductivity of the whole network using a capillary tube model, and (iv) evaluating how introducing bentonite into

the network as a coating of sand particles affects hydraulic conductivity.

Fig. 9.

In this model, the grains are first coated with bentonite. When bentonite finds any water, it swells and fills the pore spaces between the grains. The researchers then measured the hydraulic conductivity of the network by the law of conservation of mass at each junction in the network. They thus determined that the hydraulic conductivity of swollen bentonite was 5×10^{-9} cm/sec.

This led them to conclude that, in terms of hydraulic conductivity, compaction water content and compaction energy, WFS performs similarly to conventional clay. But, as seen in Figure 10, the hydraulic conductivity of WFS was not as sensitive to compaction conditions.

Fig. 10.

They also stated that the hydraulic conductivity of WFS with a liquid limit greater than 20 and/or a bentonite content greater than 6% was less than 1×10^{-7} cm/sec. Their obtained results also indicated that WFS is resistant to freeze-thaw and wet-dry cycling (Abichou et al. 2004).

In light of these results, we can also unequivocally conclude that WFS with low hydraulic conductivity is a promising hydraulic barrier material in terms of both restricting the water seepage volume and impeding the dissolved chemical transportation.

WFS in Other Applications

Garcia-Valles et al. (2008) created a product they called PROUSÓ to be utilized as an acoustic barrier and a thermal insulator. They generated this product from four industrial wastes: WFS, slag from the aluminum recycling process, dust from marble manufacturing, and recycled expanded polystyrene obtained from recycled packaging manufacturers. According to their results, PROUSÓ absorbs 95% of the sound in the 500 Hz frequency band. Additionally, they found that its firing temperature was approximately 1300°C and it presented behavior refractive supporting temperatures higher than 1000°C without any deformation. In the light of these results, this product, PROUSÓ containing WFS, is a promising formulation in terms of acoustic and thermal insulation (Garcia-Valles et al. 2008).

Another WFS study was carried out on thermoplastics. Thermoplastic rejects, which are

generally disposed of through burning or landfill disposal, are causing harmful emissions and having a gross negative effect on the soil into which they are dumped. El Hagggar and El Hatow (2009) suggested that instead of disposing of these hazardous materials through land filling or burning, they could be reinforced with WFS and then utilized for such applications as manhole covers, speed bumps and pavement blocks. In this application, due to its heavy metals presence, 10% WFS reinforcement gave the highest tensile strength as compared with other reinforcing elements such as regular sand (19.13 MPa). Likewise, the best flexural strength (34.3 N) was obtained with 10% WFS reinforcement; they also found that this new material became more dense as the WFS was increased. The environmental tests also proved that the ultimate product with WFS neither caused any leachate nor corroded under chemicals of high corrosivity since the melting and solidification processes facilitated the dissolution of heavy metals belonging to WFS. They concluded that this new material made up of thermoplastic rejects reinforced with %10 WFS had significant mechanical properties and also proved to be durable and environmentally friendly, thus making their use suitable in a number of alternate applications (El Hagggar and El Hatow 2009).

Similar studies conducted in several parts of the world recommend the recycling of WFS and its utilization in many applications such as ceramic formulations, appliance productions, and glass. However, compared with geotechnical applications or/and highway applications, such applications would utilize much lower amounts of recycled WFS.

Conclusion and Recommendations

The vast majority of waste foundry sand is currently being land filled, while only a small part of this material is being utilized, most of which in civil engineering applications. In this paper, the potential areas for WFS utilization have been explored through the conducting of an extensive literature search. Unlike research on reuse of other waste materials such as fly ash and foundry slag, there are currently only a handful of studies available on the topic. To date, the reluctance to utilize this material has been most likely due to the lack of knowledge regarding its engineering parameters and environmental impacts. Added to this is the lack of information and knowledge of any potential utilizations.

Since the aim of waste utilization is to eliminate the stockpiles, namely get rid of almost all generated WFS, various stages of highway construction are the ultimate areas to be considered. Using the material in low strength concrete and hydraulic barrier construction is also a favorable consideration, but remains one that is limited in its ability to reduce the stockpiles.

In conclusion, it is recommended that more research studies should be supported and that these will ultimately stimulate the utilization of this abundant material during various stages of highway construction.

References

Abichou, T.H., Benson, C.H., and Edil, T.B. 1999. Beneficial reuse of foundry by-products. Environmental Geotechnical Report 99-1, Department of Civil and Environmental Engineering, University of Wisconsin-Madison, Madison, Wisconsin, USA.

Abichou, T.H., Edil, T., Benson, C.H., and Tawfiq, K. 2004. Hydraulic conductivity of foundry sands and their use as hydraulic barriers. *Recycled Materials in Geotechnics*, pp. 186-200. doi: 10.1061/40756(149)13.

ACI Committee 229. 1994. Controlled low strength materials (CLSM), ACI 229R-94. *Concrete International*, 16(7): 55-64.

American Foundrymen's Society. 1991. Alternative utilization of foundry waste sand. Final Report (Phase I) prepared by American Foundrymen's Society Inc. for Illinois Department of Commerce and Community Affairs, Des Plaines, Illinois.

Annual Census of World Casting Production. 1991, 2003, 2004, 2005. Modern casting.

Bakis, R., Koyuncu, H., and Demirbas, A. 2006. An investigation of waste foundry sand in asphalt concrete mixtures. *Waste Management & Research*, 24(3): 269-274. doi:10.1177/0734242x06064822.

Basar, H.M., and Aksoy, N.D. 2012. The effect of waste foundry sand (WFS) as partial replacement of sand on the mechanical, leaching and micro-structural characteristics of ready-mixed concrete. *Construction and Building Materials*, Volume 35, pp. 508-515.

<http://dx.doi.org/10.1016/j.conbuildmat.2012.04.078>.

Beeley, P. 2001. Foundry technology, 2nd Edition, Butterworth-Heinemann, Boston, Massachusetts.

CWC (Clean Washington Center). 1995. Beneficial reuse of spent foundry sand (IBP-95-1). Recycling Technology Assistance Partnership (ReTAP), Seattle, Washington.

Clegg, A.J. 1991. Precision casting processes, 1st Edition, Pergamon Press, New York.

Collins, R.J., and Ciesielski, S.K. 1994. Recycling and use of waste materials and by-products in highway construction. National Cooperative Highway Research Program Synthesis of Highway Practice 199, Transportation Research Board, Washington, D.C.

Coz, A., Andrés, A., Soriano, S., and Irabien, Á. 2004. Environmental behavior of stabilized foundry sludge. *Journal of Hazardous Materials*, 109(1-3): 95–104. doi:10.1016/j.jhazmat.2004.03.002.

Cruz, N., Briens, C., and Berruti, F. 2009. Green sand reclamation using a fluidized bed with an attrition nozzle. *Resources, Conservation and Recycling*, 54(1): 45-52. doi:10.1016/j.resconrec.2009.06.006.

Deng, A., and Tikalsky, P.J. 2008. Geotechnical and leaching properties of flowable fill incorporating waste foundry sand. *Waste Management*, 28(11): 2161-2170. <https://doi.org/10.1016/j.wasman.2007.09.018>.

Dingrando, J., Edil, T., and Benson, C. 2004. Beneficial reuse of foundry sands in controlled low strength material. *Journal of ASTM International*, 1(6): 1-16. <http://dx.doi.org/10.1520/JAI11869>.

El Haggag, S., and El Hatow, L. 2009. Properties of thermoplastics reinforced with foundry sand waste. *Pract. Period. Hazard. Toxic Radioact. Waste Manage.*, 10.1061/(ASCE)1090-025X(2009)13:4(270), 270-277.

Environmental Protection Agency (EPA). 1998. Back document for proposed CPG III and draft RMAN III. EPA Report EPA530-R-98-003.

Freber, B. 1996. Beneficial reuse of selected foundry waste material. Proceedings of the 19th

International Madison Waste Conference, Dept. of Engrg. Professional Dev., University of Wisconsin, Madison, Wis., pp. 246–257.

Garcia-Valles, M., Avila, G., Martinez, S., Terradas, R., and Nogues, J.M. 2008. Acoustic barriers obtained from industrial wastes. *Chemosphere*, 72(7): 1098–1102. doi:10.1016/j.chemosphere.2008.03.039.

Guney, Y., Aydilek, A.H., and Demirkan, M.M. 2006. Geoenvironmental behavior of foundry sand amended mixtures for highway subbases. *Waste Management*, 26(9): 932-945. doi:10.1016/j.wasman.2005.06.007.

Ham, R.K., Boyle, W.C., and Kunes, T.P. 1981. Leachability of foundry process solid waste. *Journal of Environmental Engineering Division, ASCE*, Vol. 107, No. EE1, 155-170.

Highway Research Center, U.S. Department of Transportation: Federal Highway Administration. 2006. Foundry sand. American Foundrymen's Society, Inc. Illinois, <http://www.tfhrcc.gov/hnr20/recycle/waste/fs1.htm> (Oct. 2, 2006).

Kennedy, D.O., and Linne, C.L. 1987. Environmental and economical aspects of sand reclamation system. EPRI, Vol. 2, Palo Alto, California, pp. 217-228.

Khatib, J.M., and Ellis, D.J. 2001. Mechanical properties of concrete containing foundry sand. ACI special publication SP-200, American Concrete Institute, pp.733-48.

Kleven, J.R., Edil, T.B., and Benson C.H. 2000. Evaluation of excess foundry system sands for use as subbase material. Proceedings of the 79th Annual Meeting, Transportation Research Board, Washington, DC, CD-Rom, 27 p.

Javed, S., and Lovell, C.W. 1994. Use of foundry sand in highway construction. Joint Highway Research Project No. C-36-50N, Department of Civil Engineering, Purdue University.

Javed, S., Lovell, C.W., and Wood, L.E. 1994. Waste foundry sand in asphalt concrete. *Aggregates: Waste and Recycled Materials; New Rapid Evaluation Technology*, Transportation Research Record, No: 1437, pp. 27- 34.

John, E. 1992. Mineral aggregate conservation reuse and recycling. *Geotechnical Engineering*

Limited for Aggregate and Petroleum Resources Section, Ontario Ministry of Natural Resources.

Johnson, C.K. 1981. Phenols in foundry waste sand. *Modern Casting*, American Foundrymen's Society.

Lee, T., and Benson, C.H. 2002. Using waste foundry sands as reactive media in permeable reactive barriers. *Geo Engineering Report 02-01*, University of Wisconsin-Madison, 268 p.

Lovejoy, M.A., Ham, R.K., Traeger, P.A., Wellander, D., Hippe, J., and Boyle, W.C. 1996. Evaluation of selected foundry wastes for use in highway construction. *Proceedings of the 19th International Madison Waste Conference*, University of Wisconsin-Madison, pp. 19–31.

Manoharan, T., Laksmanan, D., Mylsamy, K., Sivakumar, P., and Sircar, A. 2017. Engineering properties of concrete with partial utilization of used foundry sand. *Waste Management*, In Press, Corrected Proof. <https://doi.org/10.1016/j.wasman.2017.10.022>.

Mast, D.G., and Fox, P.J. 1998. Geotechnical performance of a highway embankment constructed using waste foundry sand. *Recycled Materials in Geotechnical Applications*, ASCE, 66–85.

Mroueh, U.M., and Wahlström, M. 2002. By-products and recycled materials in earth construction in Finland—an assessment of applicability. *Resources, Conservation and Recycling*, 35(1-2): 117-129. doi:10.1016/S0921-3449(01)00126-4.

Naik, T., Singh, S., and Ramme, B. 2001. Performance and leaching assessment of flowable slurry." *J. Environ. Eng.*, 10.1061/(ASCE)0733-9372(2001)127:4(359), 359-368.

Siddique, R. 2007. *Waste materials and by-products in concrete*. Springer Science & Business Media.

Siddique, R. 2009. Utilization of waste materials and by-products in producing controlled low-strength materials. *Resources, Conservation and Recycling*, 54(1): 1-8. doi:10.1016/j.resconrec.2009.06.001.

Siddique, R., De Schutter, G., and Noumowe, A. 2009. Effect of used-foundry sand on the mechanical properties of concrete. *Construction and Building Materials*, 23(2): 976–80.

doi:10.1016/j.conbuildmat.2008.05.005.

Siddique, R., Singh, G., and Singh, M. 2018. Recycle option for metallurgical by-product (Spent Foundry Sand) in green concrete for sustainable construction. *Journal of Cleaner Production*, 172, pp. 1111–1120. <https://doi.org/10.1016/j.jclepro.2017.10.255>.

Tanyu, B.F., Benson, C.H., Edil, T.B., and Kim, W.H. 2004. Equivalency of crushed rock and three industrial by-products for working platforms during pavement construction. *Journal of Transportation Research Record*, 1874, 59-69, doi: 10.3141/1874-07.

Tikalsky, P. J., Smith, E., and Regan, R. 1998. Proportioning spent casting sand in controlled-low strength materials. *ACI Materials Journal*, 95(6): 740–746.

Tikalsky, P., Gaffney, M., and Regan, R. 2000. Properties of controlled low-strength material containing foundry sand. *ACI Structural Journal*, 97(6): 698-702.

U.S. Department of Transportation, Federal Highway Administration. 2007. Fly ash facts for highway engineers. Washington, D. C.

Yazoghli-Marzouk, O., Vulcano-Greullet, N., Cantegrit, L., Friteyre, L., and Jullien, A. 2014. Recycling foundry sand in road construction—field assessment. *Construction and Building Materials*, Volume 61, pp. 69–78. <http://dx.doi.org/10.1016/j.conbuildmat.2014.02.055>.

Zanetti, M., and Godio, A. 2006. Recovery of foundry sands and iron fractions from an industrial waste landfill. *Resources, Conservation and Recycling*, 48(4): 396-411. doi:10.1016/j.resconrec.2006.01.008.

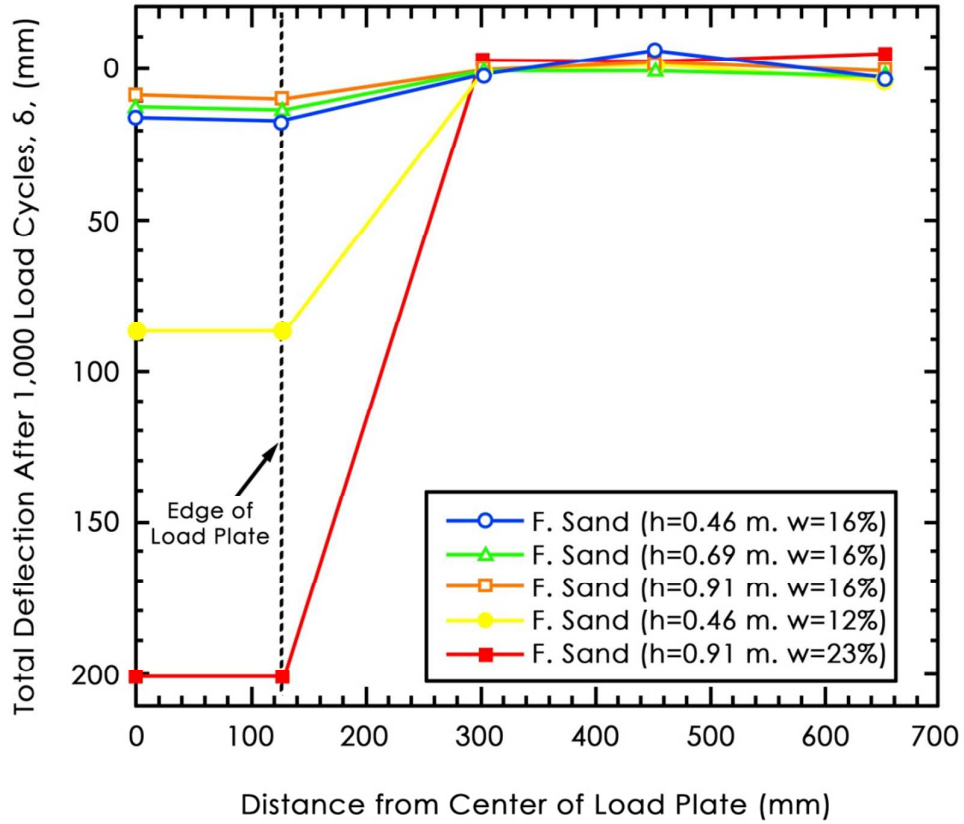


Fig. 1.

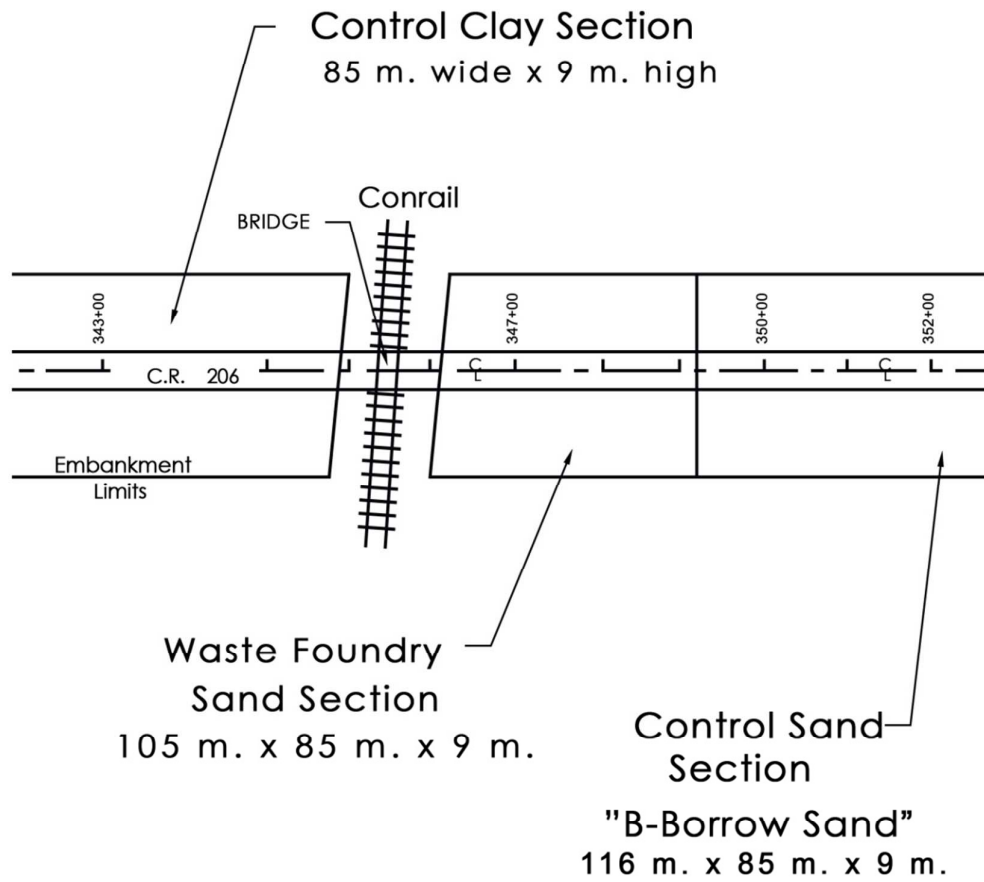


Fig. 2.

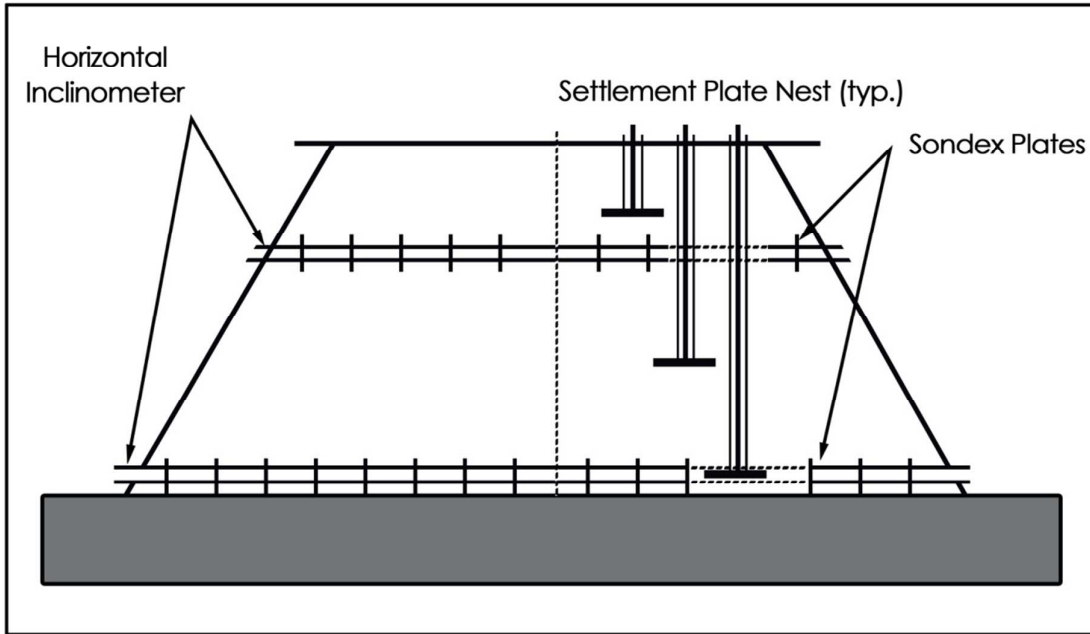


Fig. 3a.

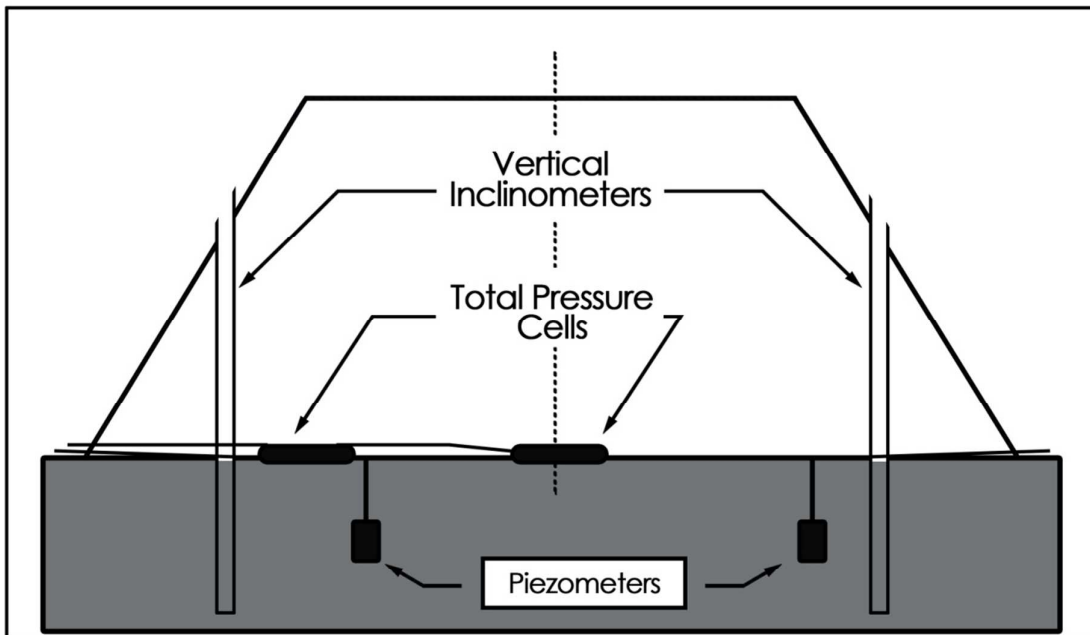
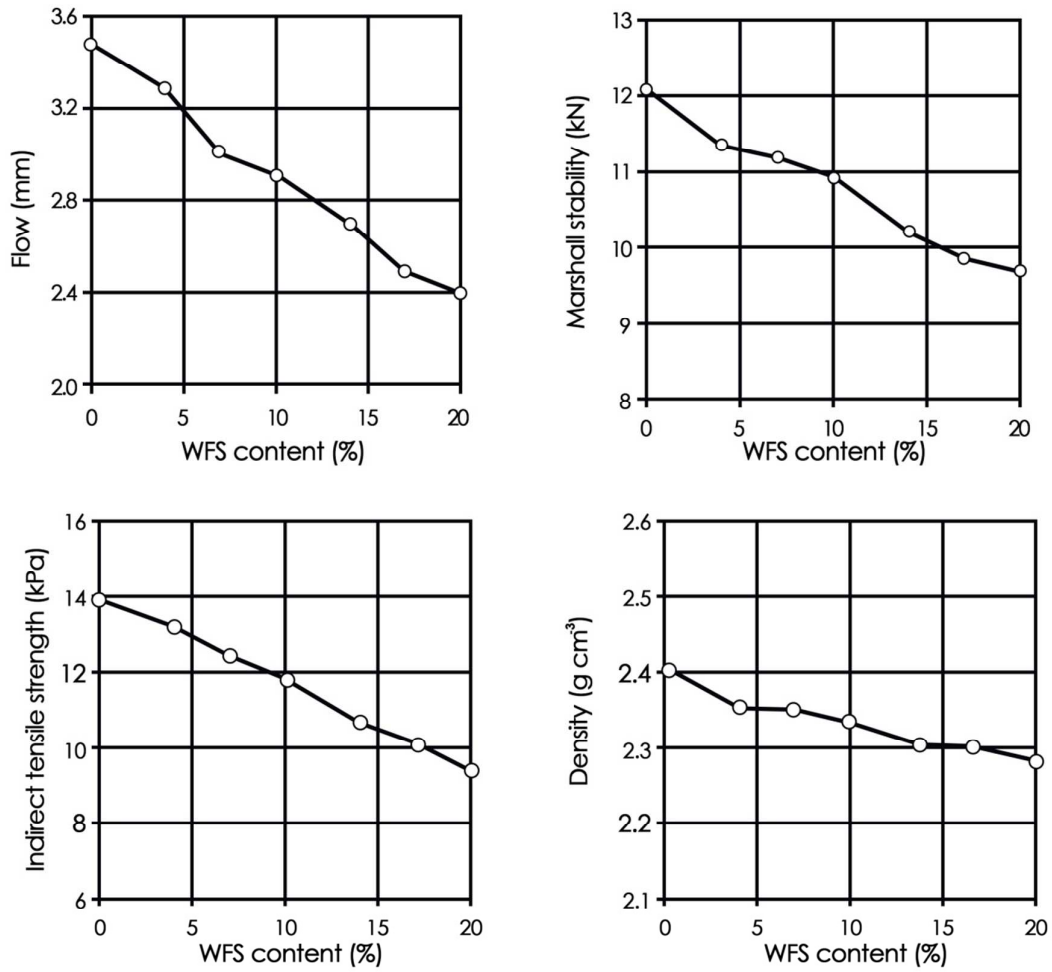


Fig. 3b.

**Fig. 4.**

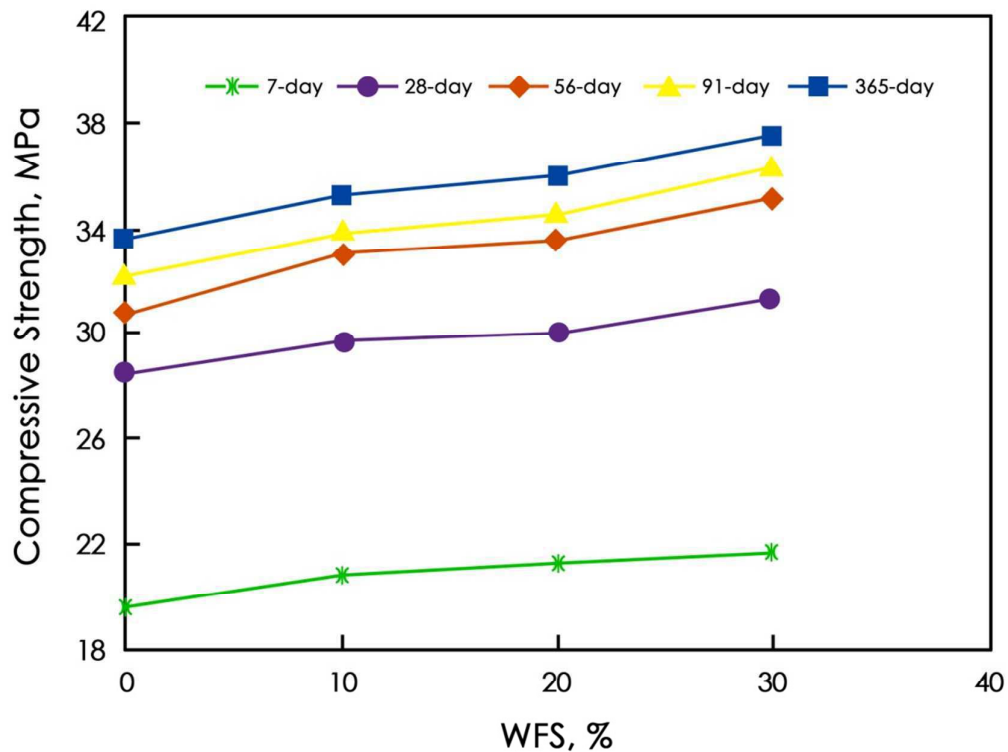


Fig. 5.

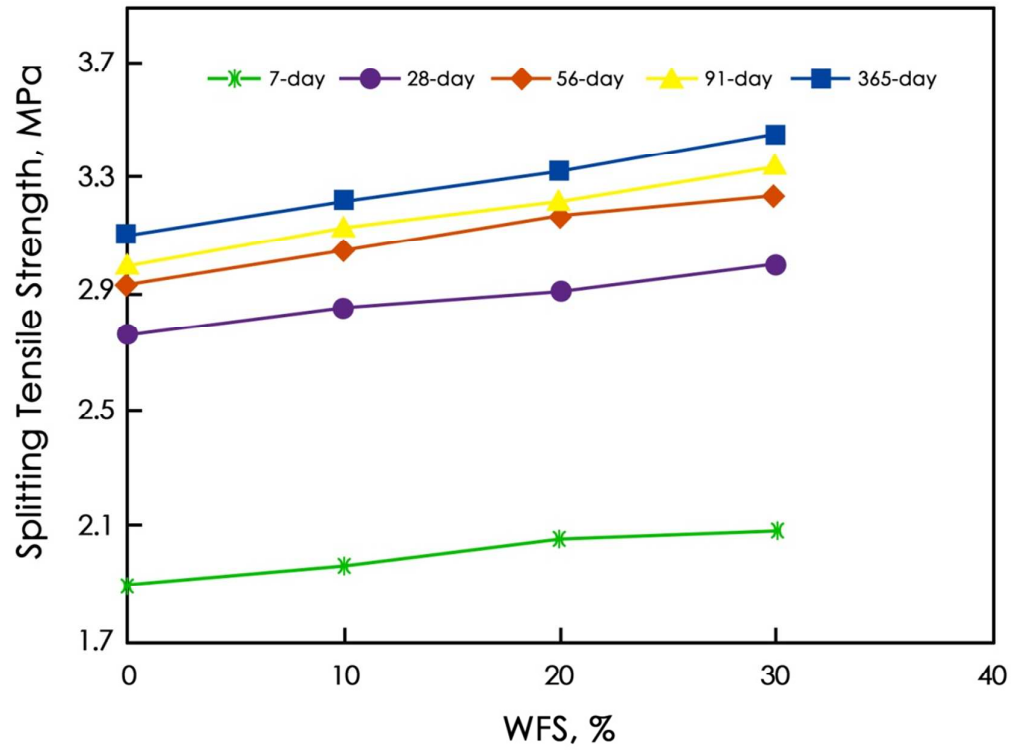


Fig. 6.

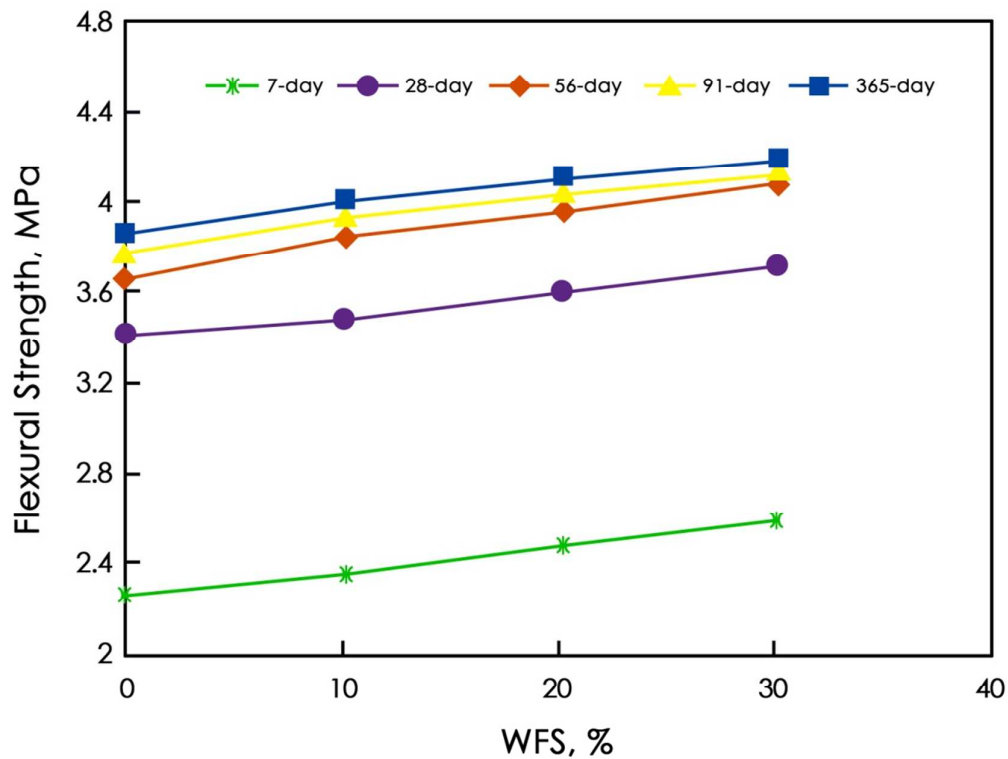


Fig. 7.

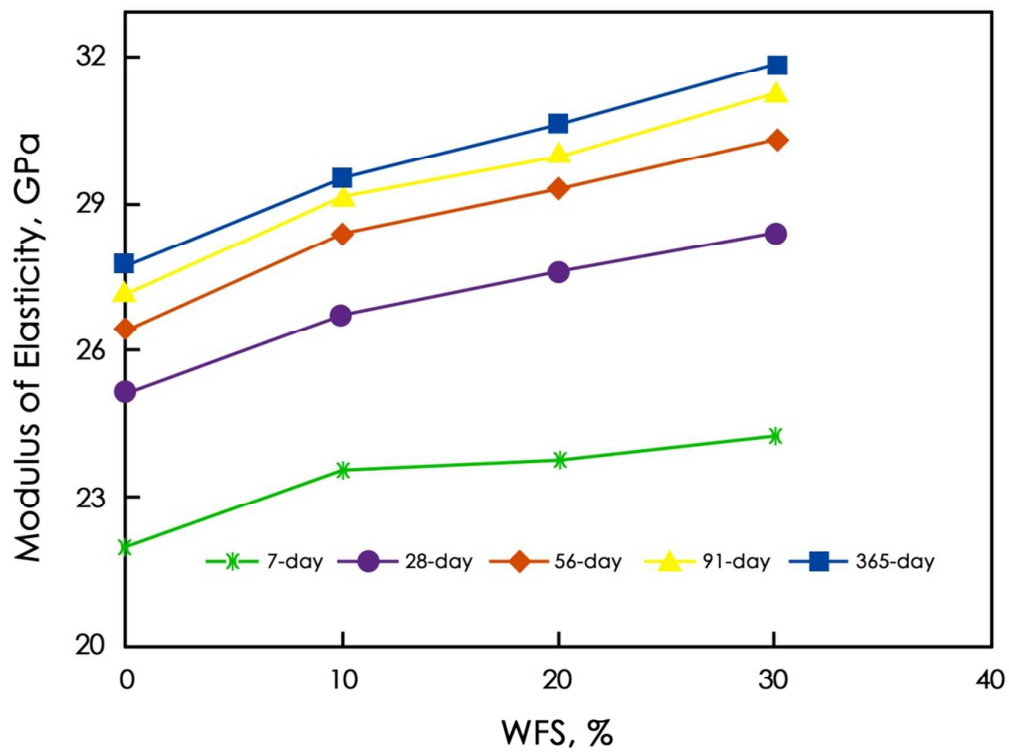


Fig. 8.

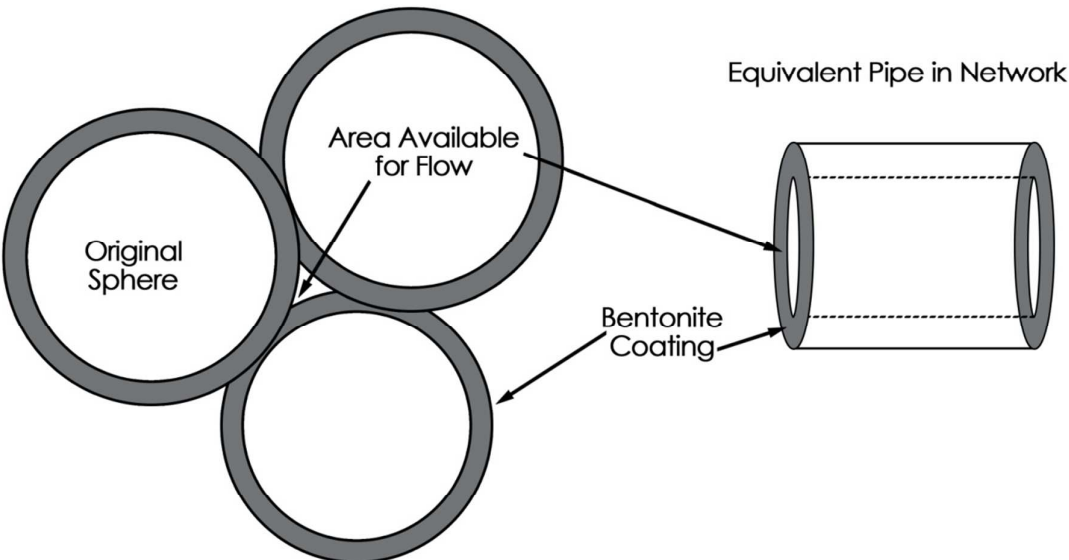


Fig. 9.

Draft

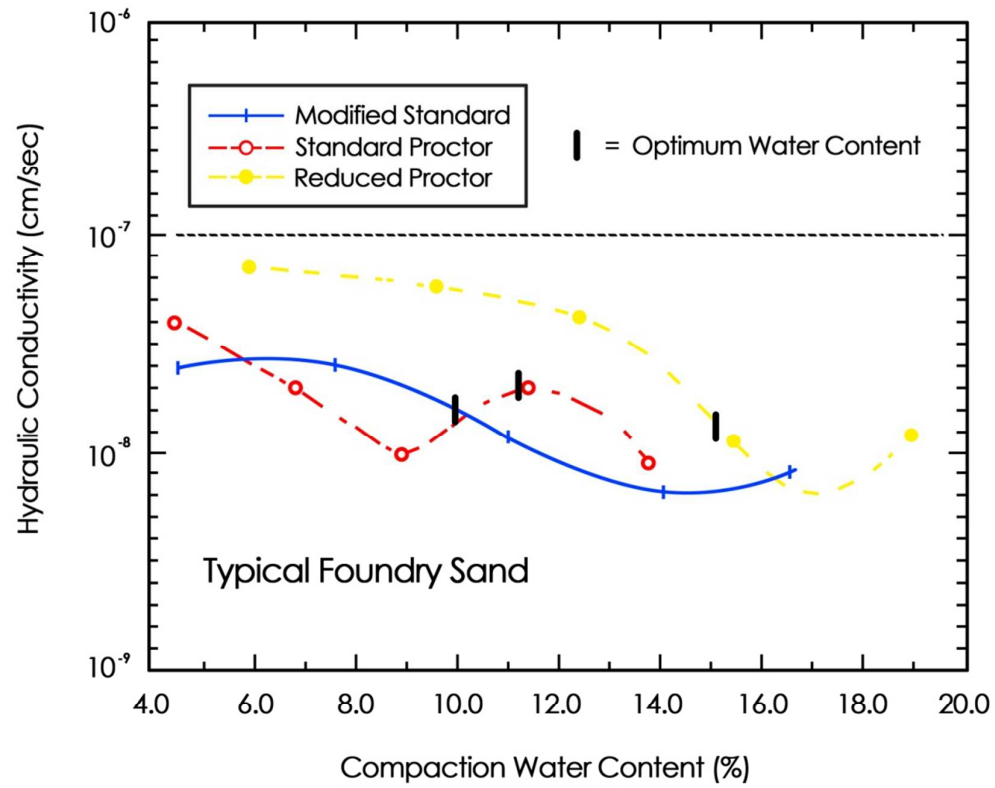


Fig. 10.

FIGURE CAPTIONs

Fig. 1. Deflection basins for WFS prepared at optimum water content (16%) and 0.46m, 0.69m and 0.91 m working platform thicknesses, 4% dry of optimum water content (12%) and 0.46 m working platform thickness, and 7% wet of optimum water content (23%) and 0.91 m working platform thickness (Tanyu et al. 2004).

Fig. 2. Plan of project site (Mast and Fox 1998).

Fig. 3a. Schematic illustration of horizontal inclinometer (Mast and Fox 1998).

Fig. 3b. Schematic illustration of vertical inclinometer and piezometers (Mast and Fox 1998).

Fig. 4. Flow, Marshall stability, indirect tensile strength, density values of WFS-asphalt cement specimens tested (Bakis et al. 2006).

Fig. 5. Compressive strength respecting WFS content and curing age (Siddique et al. 2009).

Fig. 6. Splitting-tensile strength respecting WFS content and curing age (Siddique et al. 2009).

Fig. 7. Flexural strength respecting WFS content and curing age (Siddique et al. 2009).

Fig. 8. Modulus of elasticity respecting WFS content and curing age (Siddique et al. 2009).

Fig. 9. Schematic view of introducing bentonite into network model (Abichou et al. 2004).

Fig. 10. Hydraulic conductivity of WFS (Abichou et al. 2004).

TABLEs**Table 1.** World's annual casting production (total) –in kilotons and indexes (Annual Census of World Casting Production 1991, 2003, 2004, 2005).

Annual Casting Production Volume (total) - in kilotons								
Country	Group	1991	2001	2002	2003	2004	2001:1991	1991:2001
							quotient	% change
USA	I	8839.3	11871.0	11811.7	12069.6	12314.1	1.343	34.3
Russia		18000.0	6200.0	6200.0	6200.0	6300.0	0.344	-65.6
China		10750.0	14889.0	16261.6	18145.9	22420.4	1.385	38.5
Japan		7958.7	5841.2	5751.8	6111.4	6386.5	0.734	-26.6
Total (group I)		45548.0 70.2%	38801.2 61.6%	40025.1 60.2%	42526.9 61.9%	47421.0 62.8%	0.852	-14.8
Germany	II	4336.7	4643.4	4595.4	4722.6	4984.5	1.071	7.1
France		2351.3	2527.1	3918.2	2484.5	2465.6	1.075	7.5
Great Britain		1307.7	968.2	886.3	1221.5	1273.0	0.740	-26.0
Italy		1881.5	2393.3	2440.6	2441.0	2442.3	1.272	27.2
Spain		832.7	1572.3	1628.6	1149.7	1309.2	1.888	88.8
Total (group II)		10709.9 16.5%	12104.3 19.2%	13469.1 20.3%	12019.3 17.5%	12474.6 16.5%	1.130	13.0
India	III	-	3155.0	3267.0	4038.0	4623.0	-	-
Brazil		1228.9	1760.0	1970.6	2249.4	2829.9	1.432	43.2
South Korea		1452.5	1683.2	1713.5	1783.8	1857.3	1.159	15.9
Taiwan		1454.6	1209.6	1441.4	1468.1	1451.8	0.832	-16.8
Mexico		847.0	1680.0	2030.0	1822.9	2185.2	1.983	98.3
Turkey		553.8	905.8	921.6	955.0	982.0	1.636	63.6
Total (group III)		5536.8 8.5%	10393.6 16.5%	11344.1 17.1%	12317.2 17.9%	13929.2 18.4%	-	-
Czech Rep.	IV	1327.0	471.9	441.2	477.1	522.4	0.356	-64.4
Poland		815.8	745.2	660.1	729.4	804.5	0.913	-8.7
Romania		850.5	365.0	365.5	365.5	207.0	0.429	-57.1
Hungary		93.6	121.6	136.8	253.0	164.9	1.299	29.9
Total (group IV)		3086.9 4.8%	1703.7 2.7%	1603.6 2.4%	1825.0 2.7%	1698.8 2.2%	0.552	-44.8

Table 2. Physical properties of WFS (Johnson 1981; American Foundrymen's Society 1991; Javed and Lovell 1994).

Parameter	Value	Test Method
Specific Gravity	2.39-2.55	ASTM D854
Bulk Relative Density, kg/m ³ (lb/ft ³)	2590 (160)	ASTM C48/AASHTO T84
Absorption, %	0.45	ASTM C128
Moisture Content, %	0.1-10.1	ASTM D2216
Clay Lumps and Friable Particles	1-44	ASTM C142/AASHTO T112
Coefficient of Permeability (cm/sec)	10 ⁻³ -10 ⁻⁶	AASHTO T215/ASTM D2434
Plastic limit/plastic index	Nonplastic	AASHTO T90/ASTM D4318

Table 3. Chemical properties of WFS (American Foundrymen's Society 1991).

Component	Value (%)
SiO ₂	87.91
Al ₂ O ₃	4.70
Fe ₂ O ₃	0.94
CaO	0.14
MgO	0.30
SO ₃	0.09
Na ₂ O	0.19
K ₂ O	0.25
TiO ₂	0.15
P ₂ O ₅	0.00
Mn ₂ O ₃	0.02
SrO	0.03
Loss on Ignition	5.15
TOTAL	99.87

Table 4. Mechanical properties of WFS (American Foundrymen's Society 1991; John 1992; Javed and Lovell 1994).

Parameter	Value	Test Method
Micro-Deval Abrasion Loss, %	<2	–
Magnesium Sulfate Soundness Loss, %	5-15	ASTM C88
Friction Angle (deg)	33-40	–
California Bearing Ratio, %	4-20	ASTM D1883

Table 5. WFS deflection values of WFS obtained from LSME and equation parameters (Tanyu et al. 2004).

Alternative Material	Water Content (%)	Thickness of Working Platform h (m)	Total Deflection δ (mm)	Equation Parameters	
				α	β
WFS	12	0.46	87	57.05 ^a	1.07 ^a
	16	0.46	17	9.93	-1.07
	16	0.69	13		
	16	0.91	9		
	23	0.91	472	691 ^{a,b}	1.07 ^{a,b}

Table 6. Suggested mixture calculation for CLSM (Dingrando et al. 2004).

Bentonite Content of WFS (%)	Water (kg/m ³)	WFS (kg/m ³)	Cement (kg/m ³)	Fly Ash (kg/m ³)
6-10	475	1300	50	0
10-13	500	1225	45	0
0-6	475	1000-1250 ^a	40 ^b	150-400

Notes: ^a depends on the fly ash content, ^b depends on the pozzolanic index of the fly ash (Dingrando et al. 2004).