IOP Conference Series: Materials Science and Engineering

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To cite this article: M F Iqbal *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **474** 012042

IOP Conf. Series: Materials Science and Engineering 474 (2019) 012042 doi:10.1088/1757-899X/474/1/012042

Experimental study on the utilization of waste foundry sand as embankment and structural fill

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Abstract. Metal casting industries, either ferrous or non-ferrous, produce a large quantity of the waste foundry sand (WFS). Currently, it is either discarded to landfill or collected by waste organizations to extract iron remnants after washing. This research evaluates the reuse of WFS as a replacement of sand in structural fill and embankments. Sand was used to replace WFS at a replacement level of 0, 4, 6, 8 and 10% by weight. Geotechnical and environmental tests were performed to assess the durability and physical properties of WFS samples. Features like the gradation and friction angle were similar for the samples having varying sand percentages. Moreover, the California bearing ratio indicated that WFS having 10% sand replacement will make the hardest fill material. However, it is recommended to use WFS with 6% sand replacement, since it best meets the criteria of specific gravity, optimum moisture content, maximum dry density, permeability and the California bearing ratio for structural fill, embankment and road sub-base material. The chemical composition of WFS indicated the absence of any hazardous material, which may hinder its use as fill material.

1. Introduction

Ferrous and non-ferrous metal casting foundries generate large quantities of by-products [1]. These foundries utilize silica sand mixed with some binder for their molding and casting process [2]. The repeated utilization of high-quality silica sand for casting and molding results in the production of waste foundry sand (WFS) [3, 4]. The annual generation of WFS is approximately 9 and 12 million metric tons in Europe and the United States, respectively [5, 6].

Moreover, countries such as Australia, China, and Taiwan are also generating millions of tons of WFS every year which are posing an environmental threat, since they are dumped into landfills [3, 4]. The landfilling cost of WFS is US$135-675 per ton which includes transportation, storage, and labor costs [7]. The considerable disposal cost has made the current practice of WFS disposal unsustainable for foundries [7]. Due to the lack of information and regulations on the beneficial reuse of WFS, only 32% of WFS is utilized for construction practice.

The consumption of river sand, in the construction works, is high. Therefore its demand is also very high [8]. Several countries are facing problems in meeting the demand for river sand for construction [8, 9]. Multiple pieces of research have been conducted to study the use of WFS in construction as a replacement of river sand.

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The application of WFS can be subdivided into three classes namely concrete, highways and geotechnical or soil based applications [8]. The California bearing ratio(CBR), compaction, resilient modulus and hydraulic conductivity tests on WFS and its blends with geosynthetics [4] indicated that it is suitable to be used as highway sub-base material [5, 10]. Arulrajah *et al*. [3] determined the geotechnical properties (optimum moisture content (OMC), CBR, maximum dry density (MDD), permeability) of WFS and compared them with those of a standard recycled glass waste material. It was concluded that WFS could be used as fill material in embankment and pipe bedding.

Researchers have concluded that replacing fine aggregates with a certain percentage of WFS has improved the compressive and split tensile strength, modulus of elasticity (MOE), abrasion resistance [1, 2, 11-13] and durability properties, i.e. resistance to carbonation and chloride penetration of concrete [14]. The percentage of WFS successfully replaced in concrete ranges from 5% to as high as 30%. Siddique *et al*. concluded that there was an increase of 9.8% and 9% in the compressive strength and splitting tensile strength, respectively for the concrete mix containing 30% WFS compared to the standard mix (0% WFS) [11]. At 28-days, the flexural strength of control mix (0% WFS) was 3.41 MPa and increased by 9% (4.18MPa) for the concrete mix (30% WFS) [12]. The mechanical properties of concrete containing WFS also improve with age. The modulus of elasticity of concrete mixtures (containing 0-20% WFS) increased by 6.02-12.37% at 91 days compared to 28 days average MOE of 29.9 GPa [13]. The chloride ion permeability of concrete decreases with the increase in WFS content. At 28 days, the charges passed were 1368, 1250, 1150 and 1060 coulombs at 0, 5, 10, 15% WFS content [1].The replacement percentage proposed to achieve the desired strength varies depending on the type of WFS, additives and testing conditions.

A problem with using foundry sand is the potential for environmental impact caused by the leaching of heavy metals present in the foundry sand [15]. Therefore, past researchers have studied the environmental characteristics such as chemical composition and leachate analysis of WFS and rendered that if water comes in contact with WFS during drainage, the quality of water will not be affected [3, 5].

The majority of the past research work focused on the properties of blends in which WFS was used as a secondary component, rather than sole properties of WFS [3]. If WFS fulfills the desired requirement, it can be used without mixing any other material, consequently saving a lot of cost and time required for the mix design and blending [3]. However, it has been observed that properties of pure WFS may deviate from standard criteria because of the presence of impurities and various binders used by different sources.

In this research, geotechnical investigations, including specific gravity, size gradation, permeability, direct shear, compaction and CBR tests were carried out on WFS samples containing 0, 4, 6, 8 and 10% by weight sand replacement. The chemical composition of WFS sample was also determined to ensure its sustainable use. The results were benchmarked against the standard parameters cited in the previous researches or codes. Finally, the WFS mixture having a minimum sand percentage, which can be utilized as fill material, is proposed.

2. Experimental

2.1. Materials

2.1.1. Waste foundry sand. WFS used in this study was delivered in bags from a metal casting foundry. It was black due to the presence of contaminant and burning during the metal casting process. It was chemically bounded using phenolic urethanes before using for casting process by industry. It was washed with fresh water twice and placed in sunlight for two days before testing [8].

2.1.2. Fine aggregate. Locally available river sand was used as fine aggregate, having a maximum size of 4.75 mm, confronting to the ASTM C33 requirement. The particles of the sand were round in shape and had a smooth texture. The clay and silt content was low due to excessive washing in the river. It was tested based on ASTM C128 and C136. The physical properties and mineralogy (obtained by petrographic modal analysis) of the aggregates are listed in tTable 1 and 2, respectively.

Table 1. Physical properties of the fine aggregates.

Property	Specific gravity	Fineness modulus	Water absorption %	Moisture content %	Maximum size (mm)
Values	2.65	3.06	1.48	0.14	4.75

Table 2. Petrographic modal analysis of the fine aggregates.

Mineral	Quartz	Amphibole	Quartzite + polygrain quartz	Granite	Feldspar	Biotite	Slate/ argillite
Percentage (%)	63.0	6.0	5.0	3.5	8.5	3.5	2.0
Mineral	Carbonate	Magnetite	Acid to intermediate volcanic	Muscovite	Chert	Lithic arenite	Epidote
Percentage (%)	3.0	1.0	1.0	1.0	0.5	1.0	0.5

2.2. Preparation of specimens
Five WFS specimens (GS-1, GS-2, GS-3, GS-4, and GS-5) were prepared at room temperature having 0, 4, 6, 8 and 10% sand by weight as replacement of WFS, respectively. Special care was taken for handling, transportation and placing during the testing procedure since the samples were very fragile.

2.3. Testing methods
An X-ray diffraction analysis was performed to determine the chemical composition of WFS. The hazard category of WFS was defined based on the Environmental Protection Authority standards and ASTM D3987. The environmental properties of the filtrate were analyzed for different metals.

The particle size distribution of the specimen was obtained using the ASTM D6913. A 500 g sample was used so that the overloading limits for each sieve were satisfied. The specific gravity was determined according to ASTM C128. 100 g oven dry samples were used along with a 500 mL pycnometer.

To estimate the MDD and OMC, the standard Proctor test following ASTM D698 was performed. For each specimen, GS-1, GS-2, GS-3, GS-4, and GS-5, four different sub-samples having a moisture content of 8, 10, 12 and 14% were prepared.

Shear strength is an important parameter required for the determination of the bearing capacity of the soil. The direct shear strength test was performed on the specimen following ASTM D3080. Two shear tests were performed on each of the five samples at 10 and 20 lbs standard loads. The friction angle and cohesion of the samples were also calculated.

The constant head permeability test was conducted to determine the hydraulic conductivity of the samples according to ASTM D2434. Sand was compacted in three layers in a 152 mm-diameter mold by applying a standard compaction effort.

The CBR test was carried out following ASTM D1883. All the samples were tested at their OMC. The CBR values of 2.54 and 5.08 mm were recorded using stress-penetration curves, and the highest value is reported in the study.

3. Results and Discussion

3.1. *Geotechnical properties*

The geotechnical properties of WFS and mixtures with sand were determined to evaluate its use as structural and embankment fill. The results are discussed below.

3.1.1. Grain size distribution. Figure 1 represents the grain size distribution of the five test samples and ASTM C33 limits for the fine aggregate. Approximately, 80% of the particles, for each of the five specimens, lie between 0.08-0.8mm. WFS used as an embankment, and structural fill has the particle size ranging from 0.2-1mm [16]. Percentage of the fines lies between 1.8-2.2%. The gradation curves for the samples are consistent with the curves reported for the 17 WFS samples tested by Deng *et al*. [7]. However, GS-3 best meets the gradation criteria published in the literature [7].

The coefficient of uniformity (Cu) and coefficient of curvature (Cc) range between 1.5-2.8 and 0.6-1.2, respectively. Hence, the samples are classified as poorly graded. A similar classification was reported and compared with recycled glass which is well accepted as a waste material by Arulrajah *et al*. [3]. Owing to the low percentage of fines, the Atterberg limits cannot be applied to the samples and are termed as non-plastic [3].

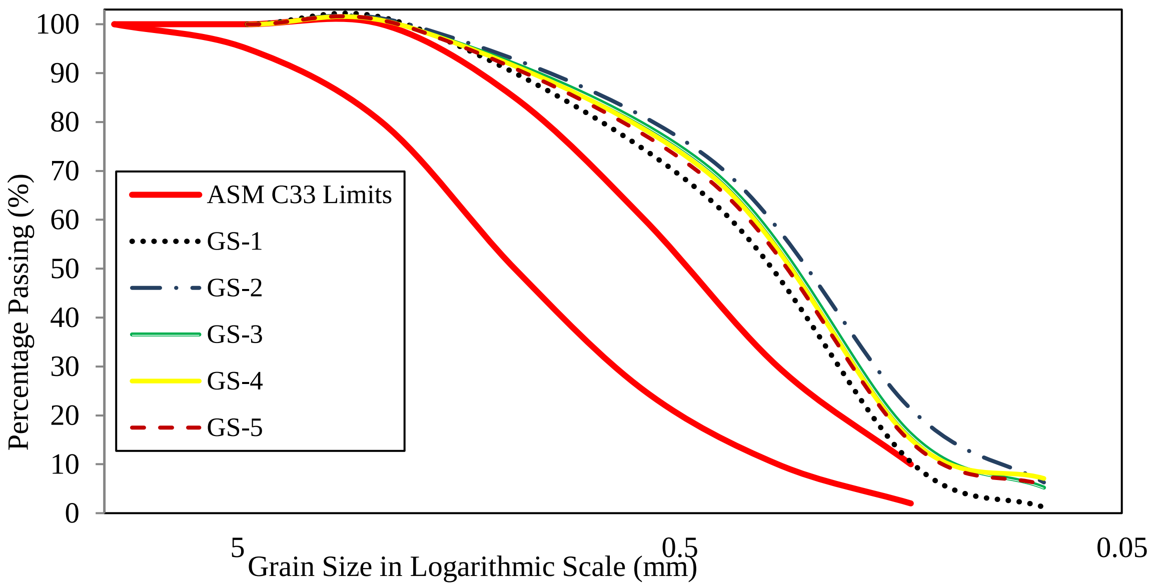

Figure 1. Gradation curves of the WFS specimens and standard fine aggregates.

3.1.2. Specific gravity and compaction characteristics. The specific gravity of the specimens lies in the range of 2.5-2.66. Sand commonly used as structural and embankment fill has a specific gravity of 2.50-2.80 [16]. The variation in the specific gravity and MDD with varying sand content is due to the variation in sand mineralogy, particle gradation, grain shape and fine content [7].

Table 3. Optimum moisture content and maximum dry density results.

Designation	GS-1	GS-2	GS-3	GS-4	GS-5	Benchmarked standard [17]
Optimum moisture content (%)	10.86	12.45	11.92	12.06	12.85	10
Maximum dry density (kg/m^3)	1810	1790	1786	1800	1820	1763

The OMC shows a slight increase with an increase in sand content, which may be due to the presence of moisture and 2% fine content in the sand used (table 3). The curves shown in figure 2 are relatively flat compared to the plastic soils and similar to the curves for WFS (without clay) used as fill material [16]. The OMC and MDD of GS-3 lie in the standard range, i.e. approx. 10% and 1763 kg/m^3, respectively [16] and, therefore. GS-3 is termed as the most suitable structural and embankment fill material.

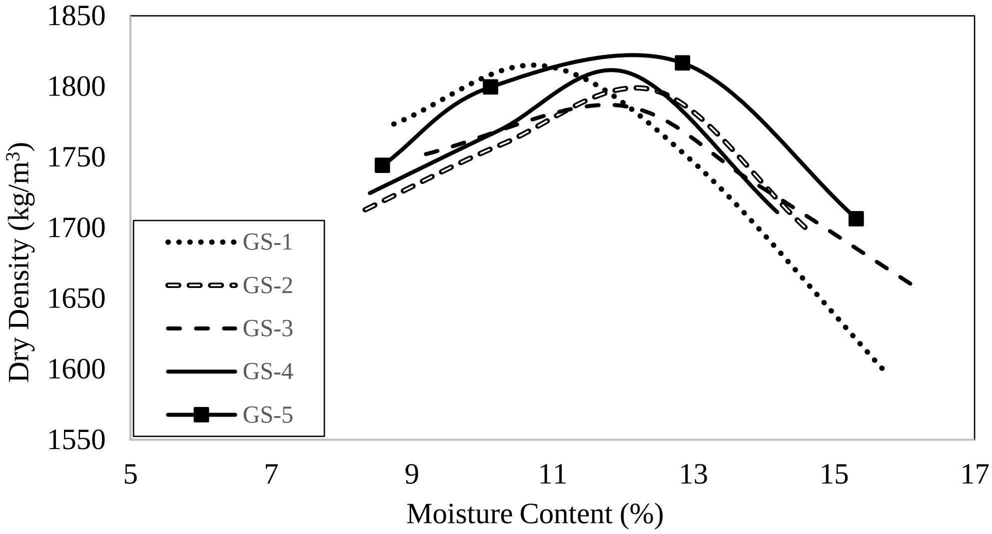

Figure 2. Compaction curves of the tested samples.

3.1.3. Shear strength. The cohesion, as shown in Figure 3, is very small as compared to the cohesion of WFS, i.e. 177 kN/m^2 (3700 psf) due to the negligible clay content in the samples [16]. The cohesion increased with the increase in sand content. This could be due to the improved density and binding with the increase in sand percentage [17].

Since the clay content is negligent, WFS used for embankment/structural fill was characterized based on the friction angle. The slight increasing trend (Figure 4) shows that as the sand content in the specimens increases, the friction angle approaches to that of the standard sand. The average friction angle is 34° for the standard sand used as a fill material [16]. The GS-3 having a friction angle of 34.2° fulfills the specified criteria.

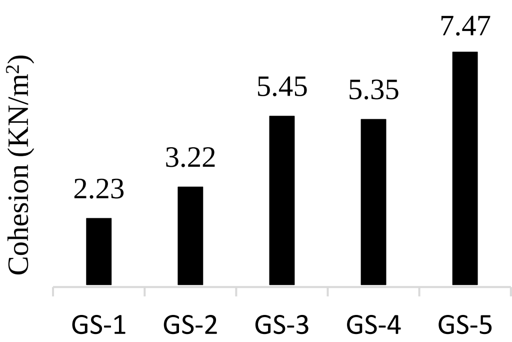

Figure 3. Cohesion values of samples.

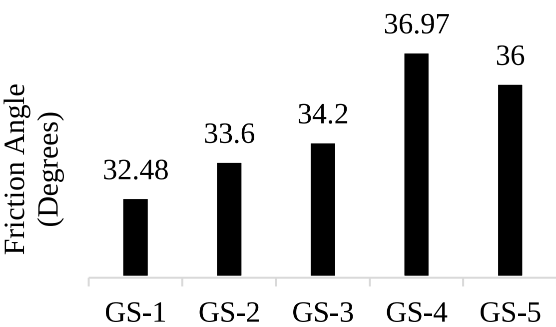

Figure 4. Calculated friction angles of samples.

3.1.4. Permeability. The permeability of WFS is lower than typical sand since it is not considered as a free draining material [3]. Table 4 shows the permeability results of the specimen. The results lie well within the range of permeability of sand used as fill material, i.e. 6x10^{-7} - 5x10^{-6} m/s [16].

Table 4. The permeability of the samples.

Designation	GS-1	GS-2	GS-3	GS-4	GS-5
Permeability x10^{-6} (m/s)	5.26	5.2	5.24	4.88	4.7

The blend of WFS with sand indicates that a high WFS content increases the water absorption due to the high fineness, surface area and porosity [18, 19]. The porosity increase results in the expansion of the pore diameter and an increase in permeability [20]. Therefore, it can be concluded from the results in Table 4 that GS-5 has the lowest WFS content. Therefore permeability is minimum. The low permeability indicates that penetration of chlorides, sulfates or alkali ions will be hindered when used as fill material and can be termed as a durable material [21].

3.1.5. California bearing ratio. The CBR values of the tested specimens lie in the range of 15-22% as shown in Table 5. For the fill material, the standard CBR is 11-30% whereas for sub-base application the requirement is 4-20 % [16].

It can be seen from Figure 5 that as the sand content increases, the stress required to achieve maximum penetration increases with GS-5 having the highest stress at maximum penetration. Thus it will make the hardest fill for roads. It can also be concluded, based on the CBR results, that WFS can be used as an alternative material for road embankment, structural fill, and sub-base material.

Table 5. California bearing ratio (CBR) of the investigated samples.

Designation	GS-1	GS-2	GS-3	GS-4	GS-5
CBR (%)	15.1	17.15	19.37	22.08	20.40

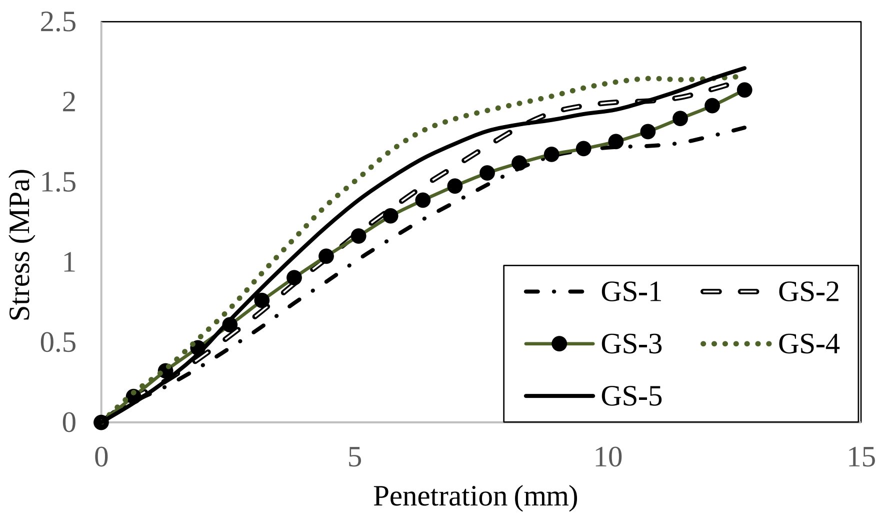

Figure 5. Stress penetration curves for the samples.

3.1.6. The chemical composition of WFS. During the casting process, WFS was exposed to molten metals at high temperatures several times. Therefore, an X-ray diffraction analysis was carried out to determine the chemical composition of WFS (Table 6). Moreover, the results were compared with similar samples reported by Arulrajah *et al*. and Singh *et al*. [3, 13]. Since the origin of the materials is sand, therefore it contains a high content of silica which improves hardness [3]. All the metals, other than iron oxide, are at a very low percentage. The presence of excess iron remnants could hinder the binding of WFS which can cause leaking problems, particularly when used as fill material. The result shows that the specimen utilized in this study has the lowest percentage of iron oxide (0.831%) among others reported in literature thereby mitigating the leakage issue. The leachate obtained from WFS does not contain any harmful metals.

Table 6. The chemical composition of WFS and its comparison with the results from literature [3, 13].

Constituent (%)	Silica (SiO_2)	Alumina (Al_2O_3)	Calcium oxide (CaO)	Magnesium oxide (MgO)	Ferric oxide (Fe_2O_3)	Chromium oxide (Cr_2O_7)	Sulfur trioxide (SO_3)	Titanium dioxide (TiO_2)
WFS	87.220	3.352	1.831	0.316	0.831	0.004	0.813	0.23
Arulrajah *et al*. [3]	84.145	11.817	1.507	-	1.533	-	0.453	0.257
Singh *et al*. [13]	83.8	0.81	1.420	0.86	5.39	-	0.21	0.22

4. Conclusions and recommendations

From the experimental observations, the following conclusions and recommendations can be made.

- ✓ The gradation results indicated that the samples are poorly graded and non-plastic. The maximum dry density (MDD) and optimum moisture content (OMC) are slightly higher than the standard fill due to variations in the sand mineralogy, particles size, shape, and fine contents.
- ✓ The cohesion of the samples is negligible due to the absence of clay content. The friction angle increased with the increase in sand content in the samples. The waster foundry sand (WFS) sample having a 6% sand has a friction angle (34.2º) similar to the average friction angle of sand used as fill material.
- ✓ The increase in sand content in WFS increased the density, thereby improving the binding and durability properties. It is owing to the same reason that WFS having 10% sand would make the hardest road embankment based on the CBR values.
- ✓ Based on the experimental evaluations, it is recommended that the WFS mixture with 6% sand can be used as structural, embankment fill and sub-base material, since its geotechnical properties (specific gravity, OMC, MDD, permeability, and CBR) are comparable to that of standard fill material.

Acknowledgments

The work was supported by the Natural Science Foundation of China (51508324), the Shanghai Chenguang Program, China (16CG06), the State Key Laboratory of High Performance Civil Engineering Materials (2018CEM006) and the Open Research Fund of State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research (IWHR-SKL-201705).

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