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ABSTRACT

Waste foundry sand (WFS) is the primary by-product of foundries. Due to metals present in WFS and negative public perception, this material is commonly discarded to landfill as a waste material. WFS can however be potentially reused as a construction material in civil engineering infrastructure projects. In order to use WFS in a sustainable manner, the engineering properties of this material needs to be properly evaluated and assessed against local requirements. In this research, geotechnical and environmental tests were undertaken to evaluate the properties and viability of WFS for usage in civil engineering construction projects. In addition, control tests were undertaken on recycled glass (RG), a well-accepted waste material that has been successfully implemented in civil engineering applications, for benchmarking purposes. Geotechnical test results, including determination of maximum dry density (MDD) and optimum moisture content (OMC), California bearing ratio (CBR) and permeability, indicate that WFS can satisfactorily be used as fill material in embankments and in pipe-bedding applications. Comparisons of the environmental test results such as chemical composition and leachate analysis, with the requirements of local authorities indicated no particular hazards in the implementation of this material in applications such as road embankment fills and pipe-bedding. The carbon footprint savings through any potential reuse of WFS/RG was furthermore quantified.

Keywords: Foundry sand; Environmental; Embankment; Subgrade; Pipe-bedding.

Abbreviations

ASLP Australian standard leaching procedure

CBR California bearing ratio

Cc Coefficient of curvature

Cu Coefficient of uniformity

D_{max} maximum particle size

Gs Specific gravity

MDD Maximum dry density

OMC Optimum moisture content

RG Recycled glass

WFS Waste foundry sand

1 Introduction

Casting and molding of ferrous and non-ferrous materials is undertaken at foundries (Salokhe and Desai, 2011). This requires specific sized high quality silica sand in order to manufacture molds used for pouring and casting molten metal. Combined application of binders and the silica sand provides a precise shape to molds (Lin et al., 2012). Typical binders used for this action include natural binders (such as bentonite clay) and chemical binders which are used for high temperature operations (Siddique and Singh, 2011). Once the desired shape is precisely generated in the mold, the molten metal is poured in. Repeated utilization of high quality silica sand for casting and molding in foundries results in the production of waste foundry sand (WFS) (Lin et al., 2012). In fact, the sand used to create the required shape in the mold is repeatedly used for the casting process until it is thoroughly contaminated, at which point the WFS is discarded, often to landfills (FHWA, 2004 and Saloke and Desai, 2011).

Waste sands are widely used in geotechnical applications and are divided into several major categories: foundry sands, raw slags, heavy ashes and metal fractions. Among these, WFS is commonly used due to its availability, mineral-rich properties and overall similarities in properties to natural and recycled sands (Saloke and Desai, 2011). Typically, WFS can be categorized into green sand and chemically bonded sand, depending on the type of binder used in casting (Siddique and Singh, 2011). Depending on the color, WFS can be distinguished on the basis of binders. Green sand colors black or grey whereas chemically bonded sand colors medium tan or off white (Siddique and Singh, 2011). As dumping this by-product is often costly, it has recently been used in applications such as hot mix asphalt fillers, cement manufacture (FHWA, 2004), embankments (Mast and Fox, 1998; Partridge et al., 1998) and road subbases (Guney et al., 2006; Goodhue et al., 2001).

Countries such as the USA, India, China, Australia and Taiwan generate millions of tons of waste WFS, which poses an enormous environmental challenge (Lin et al., 2012). The sustainable usage of WFS provides an economical and environmentally friendly solution as compared to the high costs of disposing to landfills and for quarrying virgin materials (Siddique and Singh, 2011). Partridge et al. (1999) and Guney et al. (2006) have reported that WFS material is safe to be used in some engineering applications. WFS is hydrophilic by nature and absorbs high amounts of water. Also, due to existence of phenols, this material may be corrosive (Siddique and Singh, 2011). Suitability of application of WFS in regards to environmental issues can be evaluated through leachate analysis. In the landfills for instance, precipitation and percolation of the water through deposited material generates leachate (Siddique et al., 2010). In the majority of past research, WFS was either stabilized using cementitious material (cement, lime, etc.), or used as a substitute to the sand portion of a blend, such as concrete mixture or hot mix asphalt.

Table 1 presents a summary of results of a few research works, as well as, typical properties presented in FHWA (2004). In this table, values of optimum moisture content (OMC), maximum dry density (MDD), and California bearing ratio (CBR) corresponding to specimens compacted using standard compaction effort are presented. In two of the selected research works, WFS was used solely without being mixed with other materials. In the others, however, it was blended with bentonite (Abichou et al., 2000), mixed with cement (Naik et al., 2001), or used together with geosynthetics (Guney et al., 2006). Generally, just a few research works were encountered in the literature review in which WFS was used as an individual material, instead of being mixed with other materials in a blend. In recent years, recycled materials have been evaluated and deemed acceptable in various civil engineering infrastructure applications (Arulrajah et al., 2014a). Recycled glass (RG) in particular, has made significant inroads in recent years and has been deemed suitable for applications such as embankment fills (Wartman et al. 2004), pavement subbases (Arulrajah et al., 2014b), cement treated pavement base (Arulrajah et al., 2015a), footpath bases (Arulrajah et al., 2013), as well as light-weight fill applications (Arulrajah et al., 2015b). The environmental properties of RG have also been established as being compliant with required regulatory requirements (Imteaz et al., 2012). RG is furthermore sold commercially in Australia and is marketed as a recycled sand product. RG is therefore considered an ideal material for benchmarking the performance of WFS as an engineering fill and pipe-bedding material. Conducting a series of studies on WFS, as with RG, provides the engineers and designers with adequate knowledge on properties of this material and paves the way to extensive reuse of this waste material in civil engineering projects. In this regards, comparing the properties of WFS with an approved recycled material (RG) gives a clearer appreciation of its suitability in similar applications.

Even though the majority of the WFS evaluated in the literature meet the environmental requirements, applying a leachate analysis protocol is recommended for each new source of

WFS that is intended to be used (FHWA, 2004). Furthermore, the majority of the recent research works only focus on the properties of the blends in which WFS is used as a component, rather than properties of WFS by itself. Application of WFS without mixing with other materials, if the requirements are met, can save costs and effort needed for the mix design and blending and mixture preparation. At the same time, it meets the aim of reusing WFS rather than dumping it in landfills.

In this research, the environmental and engineering properties of WFS, obtained from a recycling facility in Melbourne, Australia, were evaluated and the suitability of this material as a subgrade fill and pipe-bedding material was reported. Key gaps in recent research on WFS, such as comparisons of its properties with another widely accepted alternative recycled sand product, being RG as an engineering fill and pipe-bedding material were a primary focus of this research. The properties of WFS as benchmarked with RG will answer key remaining questions on the engineering and environmental performance of WFS as compared to other accepted recycled materials in applications such as engineering fill and pipe-bedding, and positive outcomes will lead to wider acceptance of WFS as a construction material. The carbon footprint savings through any potential reuse of WFS/RG was furthermore quantified.

2 Materials and Methods

The WFS and RG used in this research were provided from a recycling construction and demolition facility in Melbourne, Australia. The WFS was black in color, due to the presence of contaminants, during operational works. The RG was a mixed colored glass, which is too fine a material to be color sorted back into bottle-making, and thus enters the waste stream

(Arulrajah et al., 2014b). **Figure 1(a)** shows a photo of WFS while **Figure 1(b)** shows a photo of RG.

The particle size distribution of WFS was obtained using ASTM D6913-04 (2009). In addition to the sieves recommended in the standard, 2.36 mm, 1.7 mm and 1.18 mm sieves were used so that a more precise PSD was achieved. Also, 250 g samples were used so that overloading limits for each sieve according to ASTM D6913-04 (2009) was met. Specific gravity (G_s) of the material was obtained using ASTM D854-14 (2014). In this regard, 100 g of dry material was used and method B (Procedure for oven-dry samples) was applied using a 500 mL pycnometer. Deairing was done using a vacuum pump and a shaking table for agitating the slurry while it was under vacuum for two hours.

Standard compaction procedure, according to ASTM D698-15 (2015), was carried out to determine the moisture content-dry density relationship of the materials. A 101.6 mm diameter by 116.43 mm high mold was used and the specimens with 5 different moisture contents, ranging between 7 to 14%, were prepared. Each specimen was compacted in 3 layers, under standard compaction effort of 25 blows.

California bearing ratio (CBR) tests were conducted in accordance with ASTM D1883-14 (2014). A 152 mm diameter by 177.1 mm high mold was used, and WFS and RG were wetted to their corresponding optimum moisture content (OMC) and were compacted in 3 layers using standard compaction effort. In order to investigate the swelling potential of the material (existence of clay), a dial gauge was used while the CBR specimens were submerged in water for 96 hr. The CBR values at 2.54 mm and 5.08 mm penetration were then obtained using stress-penetration curves, with the higher CBR value being reported. In this regard, correction for concavity of the stress-penetration curves done following ASTM D1883-14 (2014) procedure.

Hydraulic conductivity of the materials was obtained using constant head permeability test according to (ASTM-D2434, 2006) which is applicable for granular materials. Samples were compacted in a 152 mm diameter mold in 3 layers using standard compaction effort. The head difference was 1.14 meter of water column. Permeability of a recycled/reused material is a useful measure for evaluation of its potentials for leaching.

An X-ray fluorescence test was conducted to determine the chemical composition of the WFS and RG. The hazard category of WFS was determined based on the Environmental Protection Authority (EPA, 1999 and 2010) Victoria and Australian standard leaching procedure (ASLP) (AS, 1997), which is a bottle leaching procedure. The allowable maximum particle size for this procedure is 2.4 mm, which is greater than D_{max} of materials used in this research, hence, no sieving was required. The environmental properties of the WFS were tested for different types of heavy metals by following the Australian standards protocol (AS, 1997) for the preparation of leachate, using neutral water (pH = 7) as leaching fluid. Leachate was produced by contacting the WFS and RG with the leaching fluid. This was done by placing the material in the bottle of the apparatus and adding the leaching fluid. The bottle was then sealed and mounted into an agitator to be shaken for 18 hours. The mix was then filtered using a glass fiber filter and the filtered liquid was used for leachate analysis. If the ASLP leachate concentrations are less than the specified limits, or if it can be demonstrated to be of natural origin, the WFS can be categorized as suitable for fill materials.

3 Results and Discussion

The geotechnical and environmental properties of WFS were compared with those of RG, a well-accepted recycled waste material for benchmarking purposes. **Figure 2** presents the particle size distribution of WFS and RG and also reports on other properties including maximum particle size (D_{max}), mean particle size (D_{50}), coefficient of uniformity (C_u) and coefficient of curvature (C_c). The particle size distribution curves indicate that the WFS contains about 2% fines, has a D_{max} of 2.36 mm, and has a C_c lower than 6. Therefore, it is classified as poorly graded sand while RG is well graded sand. Atterberg limit tests are not applicable for these materials, due to very low percentage of fine particles. In the majority of the research works mentioned in the introduction section, WFS was poorly graded.

Figure 3 presents the compaction curve of WFS, as well as the OMC and MDD of WFS and RG. The compaction curve shows that compared to RG, WFS has lower MDD, even though WFS has greater specific gravity value. This is attributed to the fact that the RG blend was well-graded, whereas WFS blend is poorly-graded. Also, greater OMC of WFS suggests that water absorption of this material is higher than that of RG. The MDD of WFS falls in the range of typical foundry sand (without fine particles) available in the literature (**Table 1**). However, the optimum moisture content of WFS in this research is greater than the upper range of typical WFS with no clay/silt presented in FHWA (2004). This might be due to presence of about 2% clay in the WFS used in this research. Also, OMC as high as 15.5 was reported in Partridge et al. (1999) which is well above that of WFS of this research.

No significant reading was observed on the dial gauges after 96 hours of submerging the CBR specimens in water, suggesting that these materials were non-swelling and contained negligible or low percentage of clay. CBR was then conducted on the specimens. **Figure 4** presents the stress-penetration curves for WFS and RG. CBR values for WFS were greater than the typically specified within the range of 2% to 5%. This is the local road authority specification requirements for a structural fill material in road embankments. Therefore, WFS meets the requirements to be used in road applications, to RG. Evidently, RG achieves greater CBR values than WFS, which can be attributed to its larger particle size, as well as a well-graded particle size distribution. The CBR value of the WFS is close to the lower limit of the typical WFS presented in (FHWA, 2004). However, the minimum CBR value reported in the literature was 4.3 and belongs to Kleven et al. (2000).

Hydraulic conductivity of the WFS was 5.20 x 10^{-8} m/s, which is highly lower than that of RG (9.79 x 10^{-6}). Permeability of the WFS used in this research is a bit greater than the lower limit presented in **Table 1** for typical WFS without fine particles, but falls between the range presented by Abichou et al. (2000). Generally, permeability of WFS tends to be lower than typical sand and is not therefore considered as a freely draining material (Partridge et al., 1999). This makes it suitable for construction materials where low permeability is required, such as landfill covers, liners, and even earth dam cores (Deng and Tikalsky, 2008).

A summary of the geotechnical properties of WFS is presented in **Table 2** and compared with those of RG. Generally, RG presents better properties, including higher MDD and CBR value; however, WFS also presents acceptable properties for embankment fill applications. From an engineering material perspective, the properties of the WFS coupled with its satisfactory engineering and environmental results indicate that the material is ideal for usage as a fill material in embankments or retaining, walls as well as a pipe-bedding material. The properties of the WFS used in this research are to a great extent similar to those used in previous research with satisfactory results (**Table 1**).

Table 3 presents the chemical composition of the WFS used in this research obtained from X-ray fluorescence (XRF). Total amount of major components in WFS (SiO_2, Al_2O_3, and Fe_2O_3)

is 97.50%. Major components of RG include SiO_2, CaO, and Al_2O_3 which constitute 97.69% of the blend. Evidently, both the materials contain large SiO_2 content due to their origins from sands. Generally, high amounts of SiO_2 in aggregates result in greater hardness (Siriphun et al., 2016).

A disadvantage in applications with WFS could be the potential of leaching toxic substances Leachate analysis, especially for WFS, is important since it has been exposed to melt metals in high temperatures during the casting process. This could introduce toxic metals into WFS (Guney et al., 2006). The majority of the studies carried out on evaluation of the leachate from WFS show that concentration of hazardous material was lower than the limits provided by the authorities. However, a few research works, such as (Coz et al., 2004), among others, have reported concentration of contaminants in WFS that exceeded the safety limits. This suggests necessity of conducting leachate analysis on any new source of WFS that is intended to be used for construction and have potential of leaching. **Table 4** presents the leachate analysis data of the WFS and RG and compares it to the requirements for fill material, drinking water and hazardous waste. Based on the U.S. Environmental Protection Agency, a material is considered as hazardous if any metal is present in concentrations greater than 100 times that of the drinking water standards (Wartman et al., 2004). A comparison of the leaching results indicates that all metal contaminants are well within allowable limits for the usage of WFS as a fill material. In RG, however, only for lead, the leachate concentration gets close to threshold defined by EPA Victoria for solid inert waste. But considering that the leachate values, reported in **Table 4** for WFS, are extracted using more aggressive acidic and borate solutions compared to neutral pH water, it can be expected that in case of using this material in the field and event of storm water passing through the material, the concentration of heavy metals will be less than what reported in **Table 4**. This means that the material will not pose any risk to the ground water tables or water streams beyond what is commonly accepted for fill material and solid inert waste.

Figure 5 presents a schematic and a water flow balance diagram for the usage of WFS fill material in a typical application as a road embankment fill material. Precipitation due to rainfall will hit the pavement surface layer, with some of it subsequently evaporating and the balance becoming run-off that will discharge down the slopes and into the drains provided at the bottom of the road embankment. Some infiltration will occur into the WFS fill material layer. Leachate will seep into the ground water table below; hence, the necessity for the environmental testing analysis undertaken in this research. Based on the above-mentioned leaching and engineering analyses, the WFS is found to be suitable as a non-structural fill material for road embankments. As a structural fill material in road embankments, the particle size distribution of the aggregates meets the requirements of local road authority specifications.

Evidently recycled materials will contribute to total energy savings considering the effects of embodied energy. Embodied energy is the total energy that is associated in bringing a material to its existing virgin state (Soga et al., 2011). Embodied energy is closely related to the resource depletion and greenhouse gas emission, as more embodied energy means more greenhouse gas emissions. Moreover, dumping the high embodied energy material contributes high energy depletion/waste. Hence, this parameter reflects the energy-efficiency and environmental effect of a material.

Earlier studies revealed that the use of RG as engineering material is able to save total energy related to the material up to 2 orders of magnitude, as compared to virgin aggregate-cement (EPA, 2012; Nassar and Soroushian, 2013; Tsai, 2005). WFS is a recycled waste material and is not intentionally produced for construction. Hence, the embodied energy of WFS is regarded as zero. In contrast, the embodied energy of conventional Portland cement additive is as high as 4.6 MJ/kg (Hammond and Jones, 2008). Ignoring the transportation cost (which will be close/similar to other virgin material), the total energy consumption related to the use of WFS as construction material in practice (e.g., non-structural fill material) is therefore zero, whereas that of a conventional aggregate-cement material depends on the cement dosage and weight employed in any construction project. If WFS is used to replace quarry sand resource, then based on the unit data reported by Racusin and McArleton (2012) per ton the use of WFS will save embodied energy of 81 MJ; and will reduce carbon emissions of 4.8 kg CO_2 and 5.1 kg CO_2 e.

4 Recommendations for future research

In the present research, WFS was evaluated in terms of environmental and basic geotechnical properties. It met the local authority requirements for environmental safety. However, more advanced geotechnical testing is required to investigate its suitability in a range of other civil engineering applications. Since it is a type of recycled sand, investigating the shear strength properties and compressibility of the WFS is recommended. In addition to that, blending this material with other recycled materials, such as recycled construction and demolition materials with the aim of using a 100% recycled blend is recommended. A field trial on WFS will furthermore provide conclusive evidence of actual performance of this material under actual loading conditions. In regards to environmental assessment, as some contaminants (although below specified limit) are present in the WFS sample, it is recommended to investigate whether concentrations of contaminants can be reduced through some soil treatment, i.e. soil washing.

5 Conclusions

A series of geotechnical and environmental tests were conducted on WFS and benchmarked against RG to evaluate the engineering properties of WFS and to investigate the viability of using this by-product of foundry industries in road construction. WFS were found to meet the local road authority requirements as a non-structural fill and pipe bedding material. The particle size distribution curves indicate that the WFS was poorly graded and comprised essentially of sand sized particles. CBR values for WFS are greater than the typically specified within the range of 2% to 5%, which is the local road authority specification requirements for a structural fill material in road embankments. The WFS contained a large SiO_2 content due to its origins from natural sands. Comparing geotechnical testing results of WFS with RG indicates that the properties of WFS are lower than that of RG. However, engineering properties of WFS, such as compaction and CBR values make it acceptable for fill embankment applications.

Leachate analysis results were obtained and compared with the requirements of regulatory authorities. Results indicated no environmental risks for using WFS in road applications, such as embankment fill and pipe bedding. Evidently the leachate through this material is not suitable for drinking. Pollutants in the leachate will go through diffusion and dispersion processes before it reaches the ground water source, as such concentrations of any pollutants will be significantly reduced. Such transport of pollutants can be precisely calculated using groundwater flow models, which is out of scope for this research. Moreover, the use of WFS instead of quarry sand will save embodied energy, as well as reducing carbon footprint.

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LIST OF TABLES

Table 1. Summary of the WFS properties presented in the literature

Research work	G_s	D_{max} (mm)	OMC (%)	MDD (Mg/m^3)	CBR (%)	USCS	Permeability (m/s)	Safe Environmentally	Can be used solely
Partridge et al. (1999)	2.53	-	15.5	1.43	16.8	-	$1.2*10^{-8}$	Yes	Yes
Kleven et al. (2000)	2.52-2.73	4.75	9.6-13.8	1.69-1.88	4.3-40	SP/SM (majority)	-	Not reported	Yes
Abichou et al. (2000)	2.51-2.62		10.8-12.3	1.65-1.86		SM/SC (majority)	$9*10^{-11}$-$5.3*10^{-7}$	Not reported	No
Naik et al. (2001)	2.79	2.36	-	-	-	SP	-	Yes	No
Goodhue et al. (2001)	2.52-2.68	4.75	9.6-15	1.72-1.88	-	SP-SM/ SW-SM/ SC	-	Yes	No
Typical WFS (with clay/silt) (FHWA, 2004)	2.5-2.7	1.18-4.75	8-12	1.76-1.84	11-30	SP-SM/ SP-SC	10^{-9}-10^{-5}	Inconclusive	Inconclusive
Typical WFS (without clay/silt) (FHWA, 2004)	2.6-2.8	1.18-4.75	8-10	1.60-1.76	11-30	SP	10^{-8}-10^{-4}	Inconclusive	Inconclusive

Table 2. Engineering properties of WFS and RG

Engineering Parameter	WFS	RG
Specific Gravity (G_s)	2.59	2.48
Coefficient of Uniformity (C_u)	2.06	7.5
Coefficient of Curvature (C_c)	0.92	1.5
Standard Proctor OMC (%)	12.5	12.05
Standard Proctor MDD (Mg/m^3)	1.748	1.777
CBR (%)	10.9	39
Permeability (m/s)	5.20×10^{-8}	9.79×10^{-6}

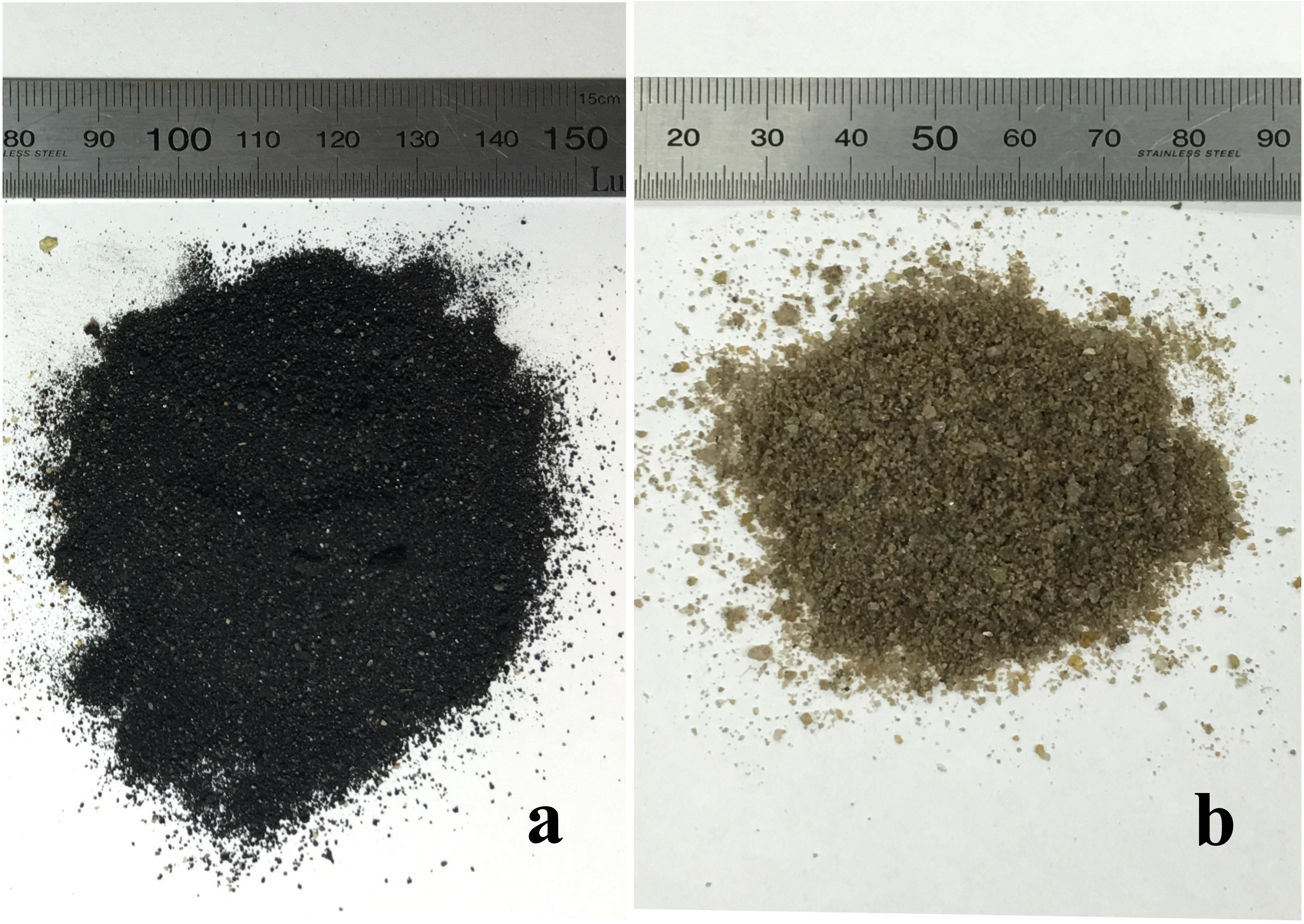
Table 3. Chemical composition of WFS and RG

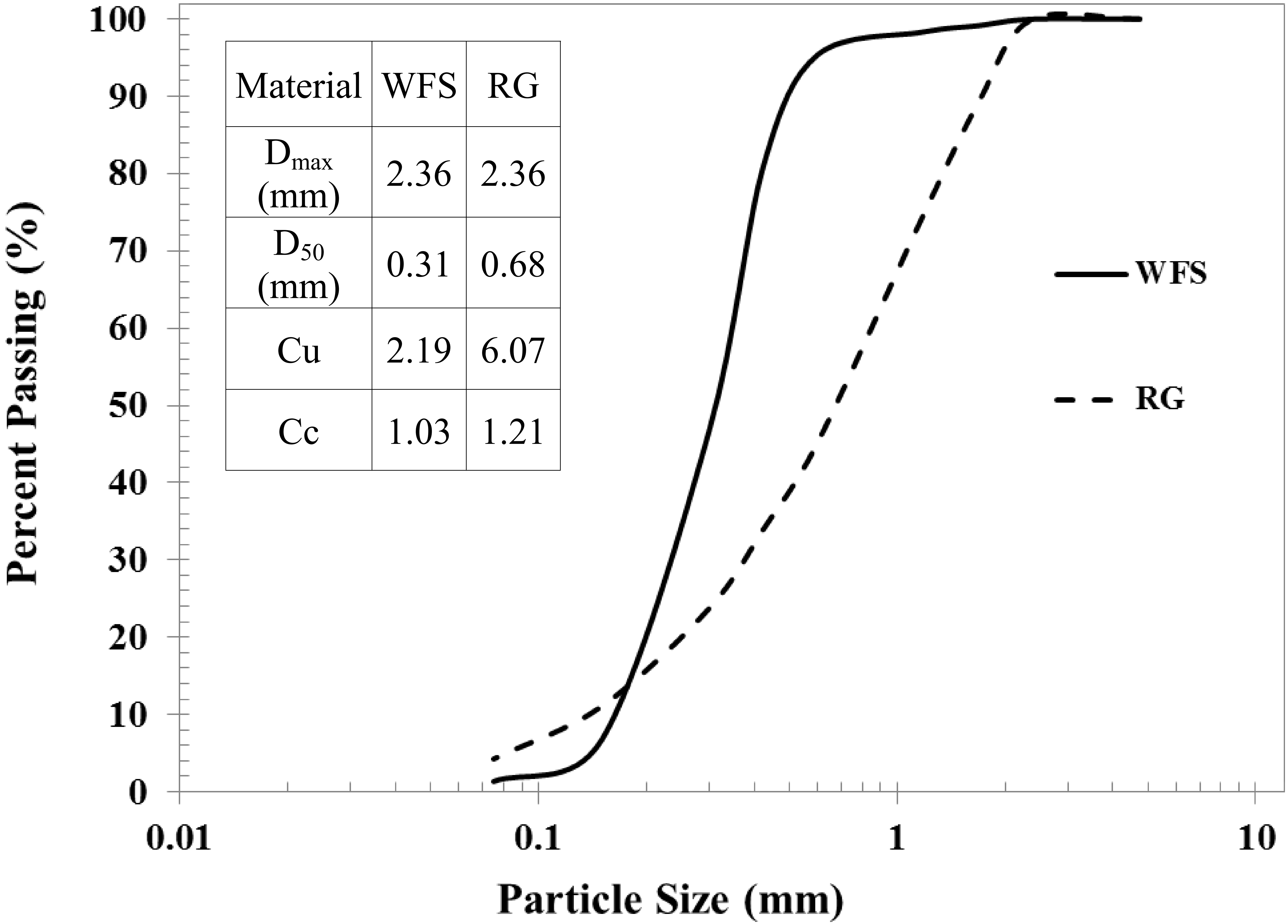
Chemical Composition (%)	WFS	RG
Silica (SiO_2)	84.145	80.124
Aluminium oxide (Al_2O_3)	11.817	3.980
Ferric oxide (Fe_2O_3)	1.533	0.688
Calcium oxide (CaO)	1.507	13.583
Sulfur trioxide (SO_3)	0.453	0.436
Potassium oxide (K_2O)	0.287	0.561
Titanium dioxide (TiO_2)	0.257	0.399
Manganese dioxide (MnO_2)	-	0.027
Chromia (Cr_2O_3)	-	0.071
Zinc oxide (ZnO)	-	0.027

Table 4. Leachate analysis data for WFS and RG.

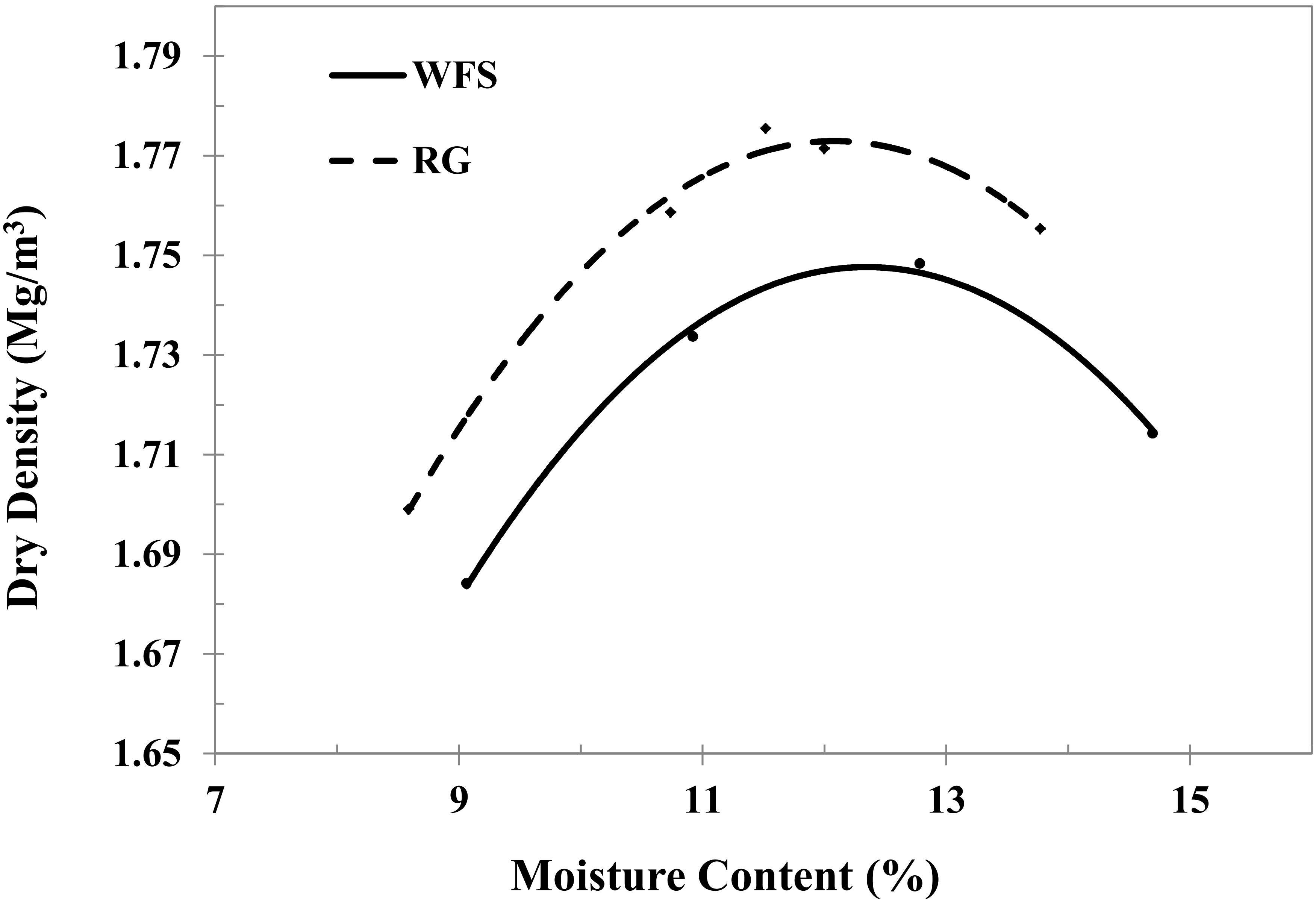
Contaminant	WFS (mg/L)	RG (mg/L)	Industrial Waste Upper Limit (EPA 2009) (mg/L)	Drinking Water Upper Limit(EPA 1999) (mg/L)
Arsenic	-	<0.01	0.35	0.05
Barium	0.133	0.1	35	2
Chromium	<0.1	<0.01	2.5	0.1
Copper	<0.1	-	100	1.3
Lead	<0.1	0.19	0.5	0.015
Nickel	<0.1	-	1	0.1
Selenium	<0.05	<0.01	0.5	0.05
Vanadium	<0.1	-	-	-
Zinc	1.067	-	150	-
Mercury	<0.001	<0.001	0.05	0.002

LIST OF FIGURES

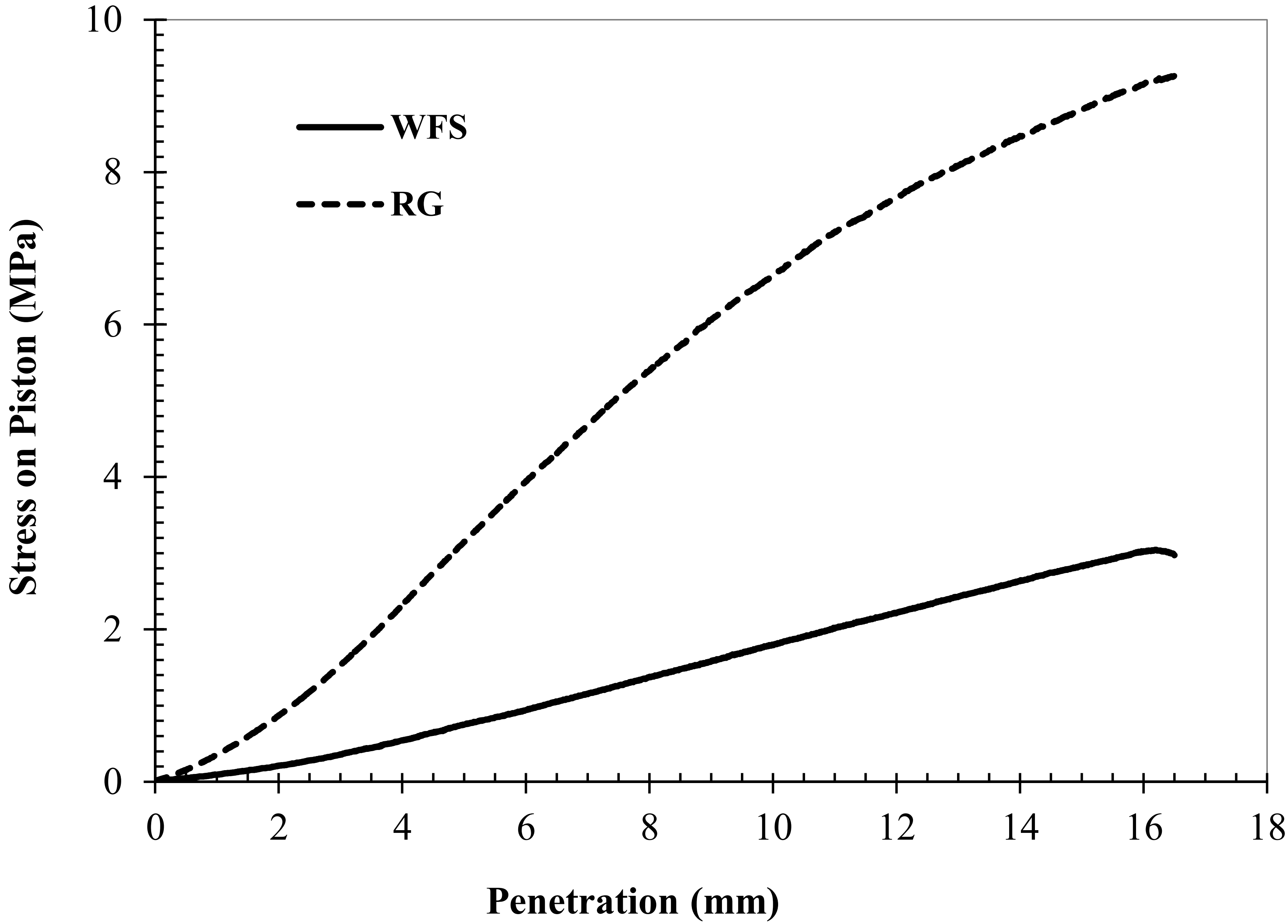

15cm
80 90 100 110 120 130 140 150
20 30 40 50 60 70 80 90
STAINLESS STEEL
a
b



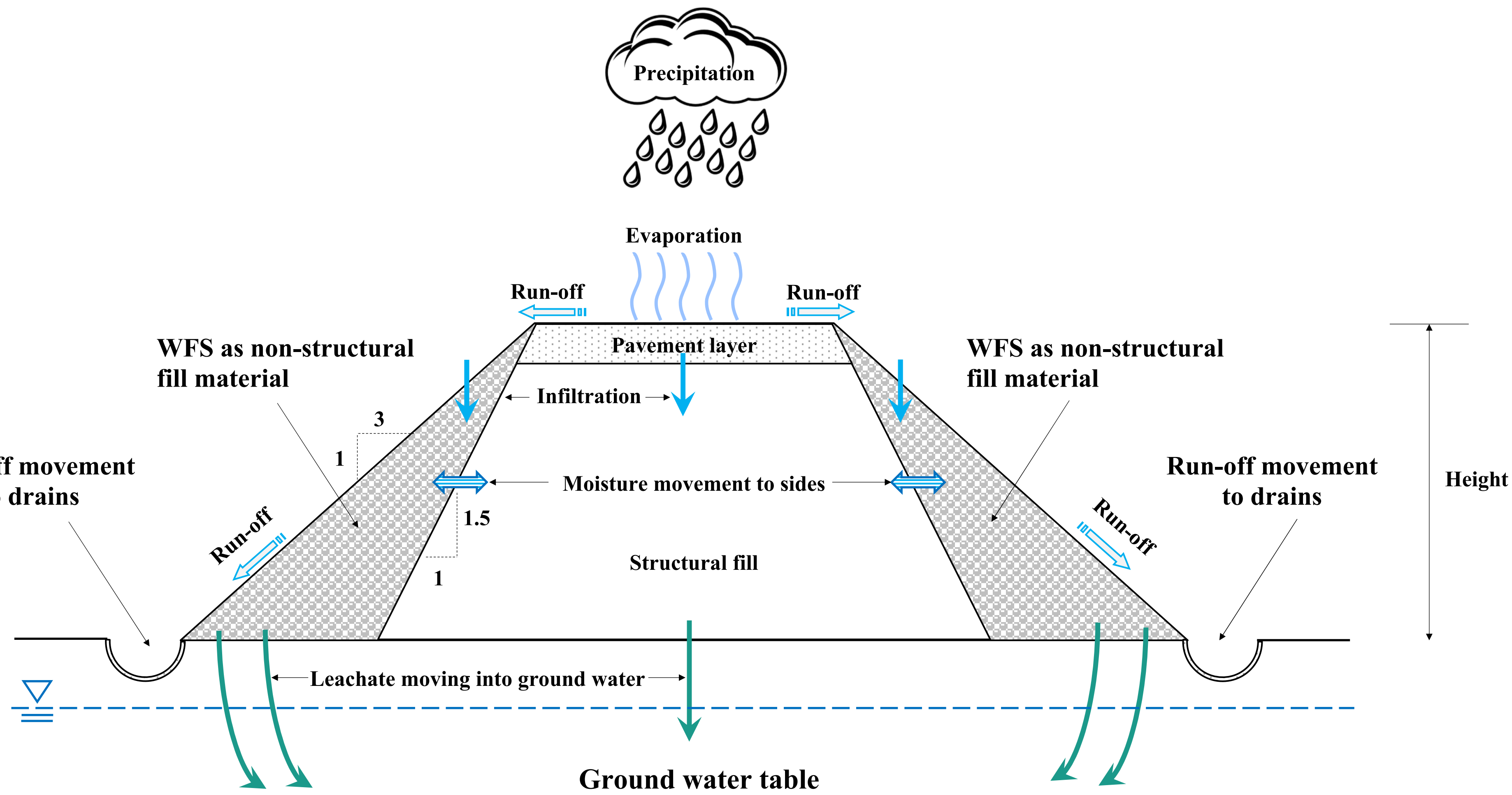
Material	WFS	RG
D_{max} (mm)	2.36	2.36
D_{50} (mm)	0.31	0.68
Cu	2.19	6.07
Cc	1.03	1.21



WFS
RG
1.79
1.77
1.75
1.73
1.71
1.69
1.67
1.65
Dry Density (Mg/m3)
7
9
11
13
15
Moisture Content (%)



WFS
RG
Stress on Piston (MPa)
Penetration (mm)
0
2
4
6
8
10
12
14
16
18



Precipitation
Evaporation
Run-off
Run-off
Pavement layer
WFS as non-structural fill material
WFS as non-structural fill material
Infiltration
3
1
1.5
1
Run-off movement to drains
Run-off movement to drains
Moisture movement to sides
Height
Run-off
Run-off
Structural fill
Leachate moving into ground water
Ground water table