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Mineralogical and Morphological Characterization of Foundry Waste Sand

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ABSTRACT

India has the third-largest foundry sector in the world, after China and the United States of America. In a foundry plant, fine river sand, water, and binders such as bentonite or resins are typically used for creating moulds of appropriate form. After the metals are cast in the mould, the non-reusable sand is disposed near the casting yard as Foundry Waste Sand (FWS). The FWS has potential applications and can be used as fill material for roads, embankments, and retaining walls or as a substitute for replacement of soft soils. Therefore, it is necessary to quantify the microstructural properties and chemical stability to be used as safe geomaterial. In the present study, seven FWS samples, collected from different foundry plants from two southern states of India were evaluated for their mineralogical and morphological properties using various spectroscopic and microscopic tools like Scanning Electron Microscope (SEM) with Energy Dispersive X-ray Analyser (EDX), X-ray Powder Diffraction (XRD), and Fourier transform infrared spectroscopy (FTIR). The morphological shape descriptors like sphericity, convexity and aspect ratio were computed using 2D image analysis. Further, leaching characteristics were obtained using Toxicity Characteristic Leaching Procedure (TCLP) to investigate the potential contamination of ground water by using FWS as fill materials. It is observed that FWS can be a potential fill material as its morphological characteristics are like that of sands and can be good candidate for use as fill material in geotechnical applications. Also, the TCLP analysis indicated that the concentration of the heavy metals leaching from the use of FWS are well within the acceptable limits. The importance of this study lies in gaining a better understanding of the micro level characteristics and degree of toxicity to support the continued usage of FWS as a sustainable geomaterial.

Keywords: Foundry waste sand, Particle morphology and mineralogy, Leaching potential, Sustainable granular geomaterial

1 INTRODUCTION

The foundry industry in India is the third largest in the world with more than 5000 foundry plants, producing over 2500 tonnes of foundry waste sand (FWS) per year. The FWS is a by-product of the metal casting process and is generated when the foundry sand (typically consists of a mixture of silica sand, clay, and other additives) is used to make moulds for casting metal parts (Dyer & Lima, 2022). After the casting process is complete, the sand is removed from the mould and can be recycled or discarded as waste. After reusing of foundry sand for maximum of three to four times, finally the FWS is then disposed in the nearby land.

Several studies have been conducted on the application of FWS as a construction material in concrete (Bhardwaj & Kumar, 2017), transportation (Dyer & Lima, 2022), and environmental aspects (Cioli et al., 2022) as a replacement for natural materials. However, it is critical to note that foundry waste sand can also contain trace amounts of metals and other contaminants that may be harmful to the environment and human health if not properly managed and reused (Siddique et al., 2010). Hence, toxicity characterization along with mineralogical and morphological characterisation of the waste material becomes necessary. Several researchers have contributed to comprehension of the micro-structural characterisation of other waste materials like fly ash (Bakare et al., 2019; Pai et al., 2021), pond ash

(Jose et al., 2020), copper slag (Sanchez & Sudbury, 2013), and municipal solid waste incineration ash (Gupta et al., 2021). However, there are limited number of studies in the case of FWS.

To evaluate the possible impacts on the environment by the reuse of FWS, identifying recycling and reuse avenues, and creating efficient waste management strategies, it is critical to characterise its mineralogical and morphological characteristics. Furthermore, considering the possibility of contaminants leaching into the environment, it is necessary to minimize the negative effects on environment. Hence, the present study was conducted to understand the mineralogical characteristics of FWS using Scanning Electron Microscope (SEM) with Energy Dispersive X-ray Analyser (EDX), X-ray Powder Diffraction (XRD), and Fourier transform infrared spectroscopy (FTIR). In addition, a morphological characterisation study was conducted, and sphericity, convexity and aspect ratio were evaluated using image analysis. Also, loss of ignition (LOI) tests was conducted to find the percentage of organic matter content present in the FWS. Finally, leachate potential was determined using Toxicity characteristics leaching potential (TCLP). The present study is significant in considering the bulk utilization of the FWS geotechnical constructions.

2 MATERIALS AND METHODS

2.1 Foundry waste sand

In the present study, foundry waste sand was collected from different metal casting facilities including three samples from Coimbatore (Tamil Nadu state), and two samples FWS from Renigunta, (Andhra Pradesh state) and two samples from Kakinada (Andhra Pradesh state) were collected in bulk quantities. In addition, one virgin foundry sand (before casting) was collected from Renigunta site. The collected samples were given with the sample ID of FWS-1 to FWS-7 and virgin foundry sand as VFS.

2.2 Material Properties

The collected FWS were tested for basic characterization which included specific gravity, pH and particle size distribution analysis and the results are provided in Table 1. All the samples were classified as poorly graded sand (SP) with the particle size distribution curve as shown in Figure 1.

Table 1. *Basic Geotechnical characterisation of foundry waste sand*

Sample ID	FWS 1	FWS 2	FWS 3	FWS 4	FWS 5	FWS 6	FWS 7	VFS
Type of metal cast	Iron	Grey iron	Ductile (SG) iron	Aluminium	Aluminium	-	-	Virgin Sand
Specific gravity	2.66	2.76	2.71	2.46	2.55	2.56	2.55	2.38
pH	8.80	9.78	10.38	8.52	7.98	7.97	8.70	8.17
% Fines	7.49	2.78	1.93	2.12	1.56	0.13	1.60	1.72
C_u	2.47	2.40	2.26	1.89	2.62	1.75	2.13	1.80
C_c	1.00	1.18	1.19	0.97	1.26	0.96	0.97	0.96
Classification	SP	SP	SP	SP	SP	SP	SP	SP

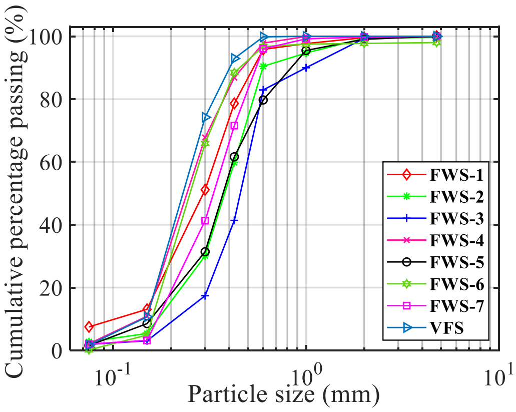


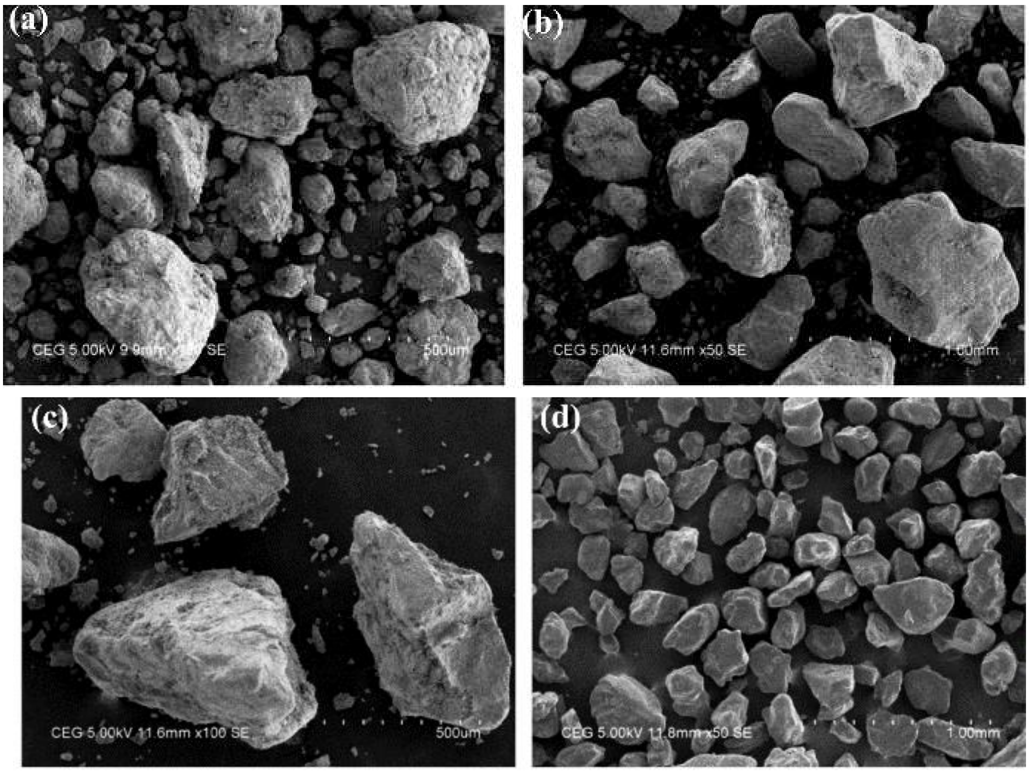
Figure 1. *Particle size distribution of different foundry waste sand*

2.3 Physicochemical Properties

2.3.1 Scanning Electron Microscope (SEM) with EDS

SEM with EDS is a technique used for analysing the chemical composition of a sample. It uses a focused beam of electrons to generate high-resolution images of the sample surface. The SEM micrographs were taken at different magnifications from x50 to x3000 shown in Figure 2. The FWS 2,3,4,5,6 and 7 have the sub angular to angular shape whereas FWS 1 and 7 have sub rounded shape. The EDS identifies the elemental composition of the sample by analysing the X-rays emitted when the sample is irradiated with the beam. SEM generates images while EDS analyses the sample, providing a detailed analysis of the sample. The EDS results are provided in Table 2. As can be observed, the silica, alumina, and iron are the major compositions and are consistent with the composition reported for FWS in the literature (Guney et al.,2006; Carnin et al.,2012).

Loss of ignition (LOI) is a measure of the amount of volatile components, such as water and organic compounds, that are present in the material. It refers to the weight loss of a material after being heated to a high temperature. Specifically, it is the weight percentage of a material that is lost when it is heated to a specific temperature (usually 750-950°C) using a muffle furnace. The FWS samples were tested for LOI according to ASTM D7348-21 standards al.,2012) as given in the Table 2.



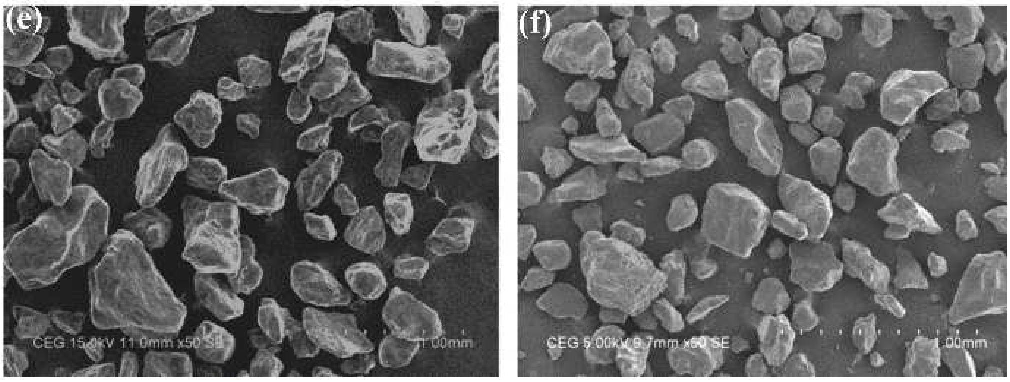


Figure 2. *SEM micrographs used for morphological studies on: (a) FWS1, (b) FWS2, (c) FWS3, and d) FWS4 (e) FWS5, (f) FWS6*

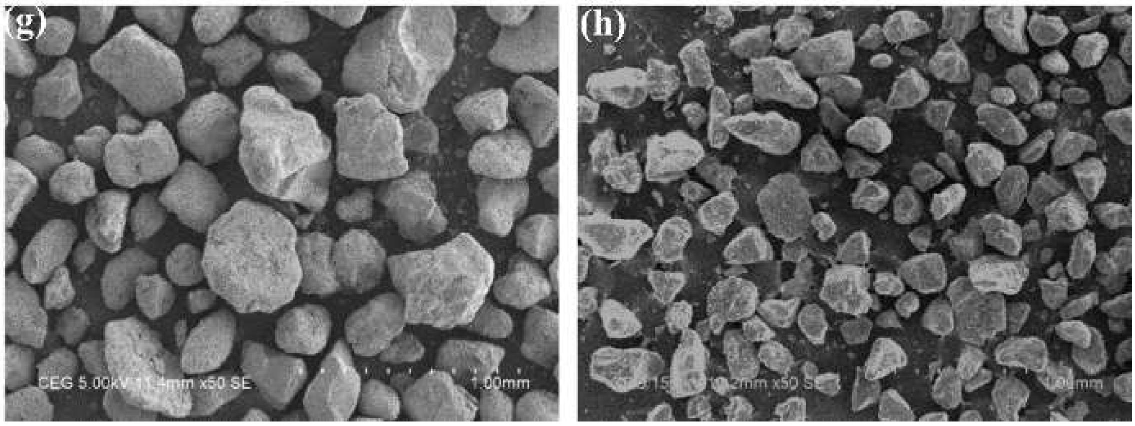


Figure 2. *SEM micrographs used for morphological studies on: (g) FWS7, and (h) VFS (continued)*

Table 2. *Elemental composition (mass %) from EDS and loss of ignition (%) of foundry waste sand*

Element	FWS 1	FWS 2	FWS 3	FWS 4	FWS 5	FWS 6	FWS 7	VFS	Guney et al., (2006)	Carnin et al., (2012)
Na	2.49	1.61	1.89	0.93	0.89	1.27	1.84	1.10	-	0.27
Mg	2.36	0.83	0.22	0.22	0.24	0.25	1.68	0.11	0.023	0.30
Al	11.32	7.99	6.65	7.61	8.20	9.57	9.07	7.43	0.8	4.21
Si	62.11	77.12	85.44	79.87	80.80	73.93	69.65	82.87	98	29
K	2.12	3.29	2.58	6.60	5.53	9.28	4.33	5.86	0.04	0.93
Ca	1.99	1.08	0.52	1.39	1.20	1.39	1.84	0.84	0.035	1.00
Ti	1.68	0.96	-	-	-	-	1.01	-	-	0.46
Fe	14.80	7.15	1.75	2.44	2.91	3.25	9.52	1.68	0.25	2.82
Ni	0.16	-	0.18	0.22	-	0.31	0.01	-	0.004	-
Cu	-	-	0.53	0.15	0.23	-	-	-	0.002	-
Zn	-	-	0.07	0.58	-	-	0.51	-	0.003	-
Pb	-	-	-	-	-	0.75	-	0.11	0.003	-
Cl	0.98	-	-	-	-	-	-	-	-	-
S	-	-	-	-	-	-	0.15	-	-	0.95
Cr	-	-	0.18	-	-	-	-	-	0.003	-
LOI (%)	8.21	1.38	0.65	2.54	2.83	3.38	1.7	2.77	4.3	3.64

3 RESULTS AND DISCUSSION

3.1 Measurement of morphological shape parameters

The shape descriptors like sphericity (S), convexity (C) and the aspect ratio (A) were calculated using 2D image analysis techniques which include raw image smoothing, binarization-grey scaling, thresholding, and computation of particle shape parameters. It is important to note that these shape descriptors can be used to identify the influence caused by various metal casting process involved in the foundry unit and natural geological processes, such as weathering, transport, and depositional processes, and can provide valuable information about the history and environment of a sedimentary deposit. The calculations for these descriptors were performed according to the method outlined in the studies by (Kalyan & Kandasami, 2021; Altuhafi et al., 2013) and the quantified shape measures were compared with the available literature.

3.1.1 Sphericity

Sphericity (for area) is defined as the ratio of the projected area of a soil particle (AS) and the area of the minimum circumscribing circle (A_{cir}) (Mitchell & Soga, 2005). If the sphericity is equal to 1.0 it indicates a perfect sphere and values lower than 1.0 indicate increasingly non-spherical shapes. The area sphericity of a particle can be computed by the following equation.

$$S_A = \frac{A_S}{A_{cir}} \quad (1)$$

The sphericity for different FWS were calculated using SEM images at various magnification ranges between x50 to x3000. The sphericity histograms of FWS are presented in Figure 3. Almost all the FWS samples have the sphericity range between 0.3 to 0.8, which lies in the classification range from subangular to subrounded (Hryciw & Zheng, 2016).

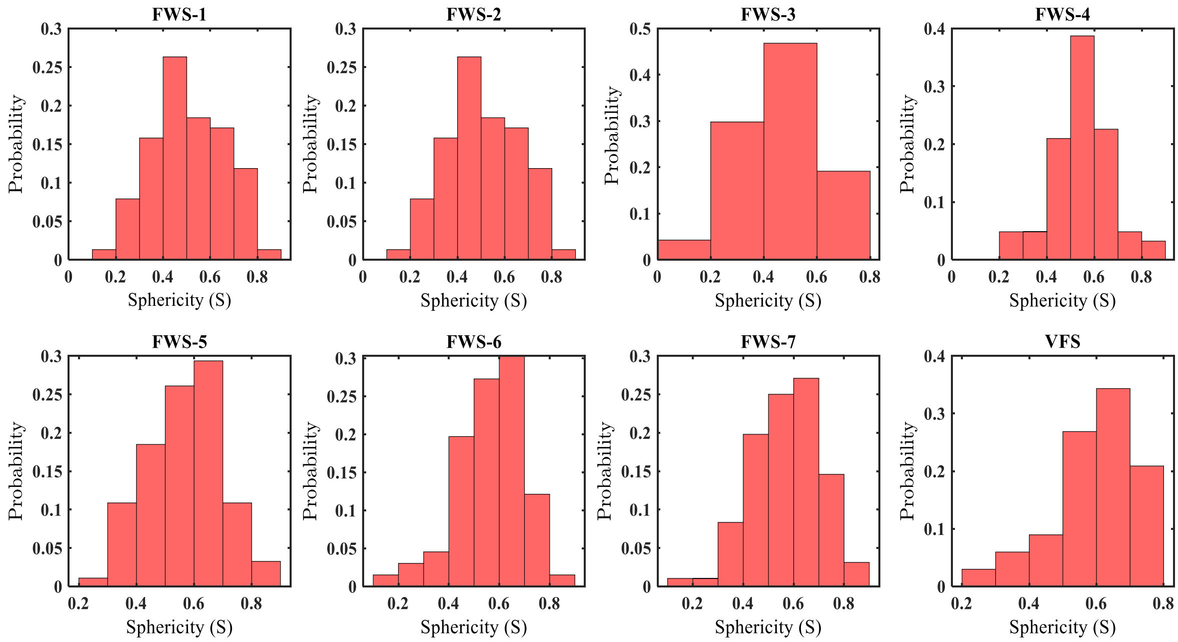


Figure 3. *Sphericity histograms of different foundry waste sand*

3.1.2 Convexity

The convexity is defined as the ratio of the area of a particle (A) to the convex area surrounding the particle (Acon). The minimum convex boundary that encloses the particles is called the convex area, which represents the area within these boundaries. A sand particle with a perfectly spherical surface would have a convexity value of 1.0, while a particle with a highly irregular would have a convexity value significantly less than 1.0. The convexity of a particle can be computed by the following equation (Rodriguez et al., 2013).

$$C = \frac{A}{A_{con}} \quad (2)$$

The convexity for different FWS were calculated using SEM images at various magnification ranges between x50 to x3000. The convexity histograms of FWS were plotted as shown in the following Figure 4. Almost all the FWS samples has the convexity ranges between 0.8 and close to 1, based on the observed convexity values the FWS particles can be classified as convex particles.

3.1.3 Aspect ratio

Aspect ratio is defined as the ratio of the shortest axis (width, d2) to the longest axis (length, d1), and it represents the shape of the particle, The aspect ratio of a sand particle is important because it affects the behaviour of granular materials. A higher aspect ratio indicates that the particle is more elongated, while a lower aspect ratio indicates that the particle is more spherical. The aspect ratio of a particle can be computed by the following equation (Cavarretta et al., 2010).

$$A = \frac{d_2}{d_1} \quad (3)$$

The aspect ratio for different FWS were calculated using SEM images at various magnification ranges between x50 to x3000. The aspect ratio histograms of FWS were plotted as shown in Figure 5. Almost all the FWS samples have the aspect ratio range between 0.6 and 1. Based on the observed aspect ratio values the FWS can be classified as rounded particles.

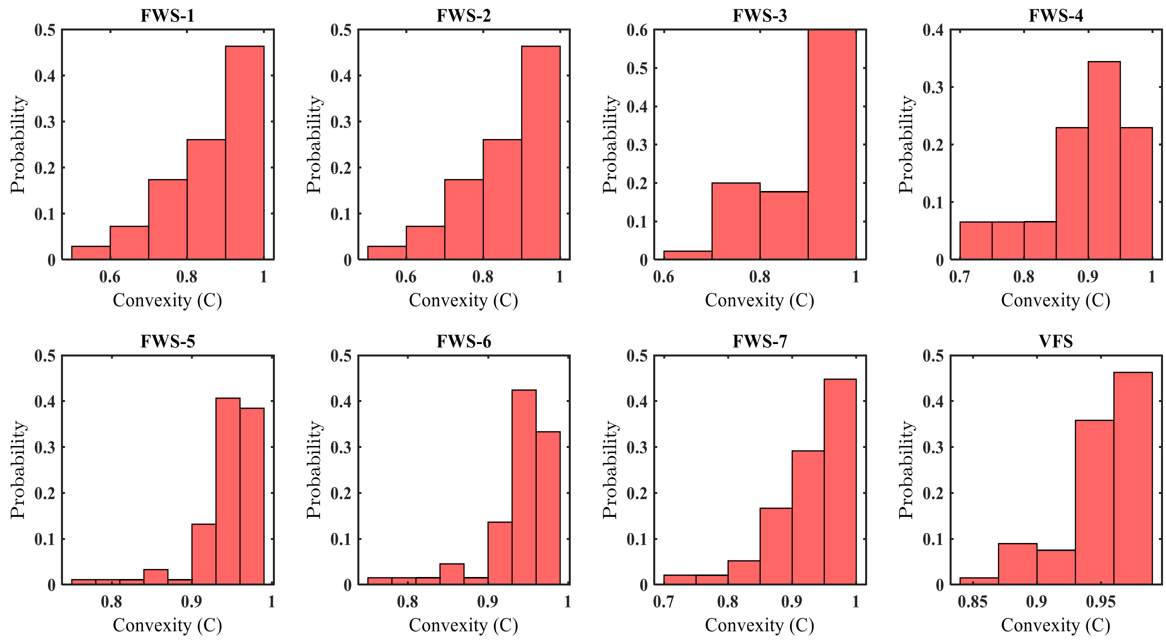


Figure 4. *Convexity histograms of different foundry waste sand*

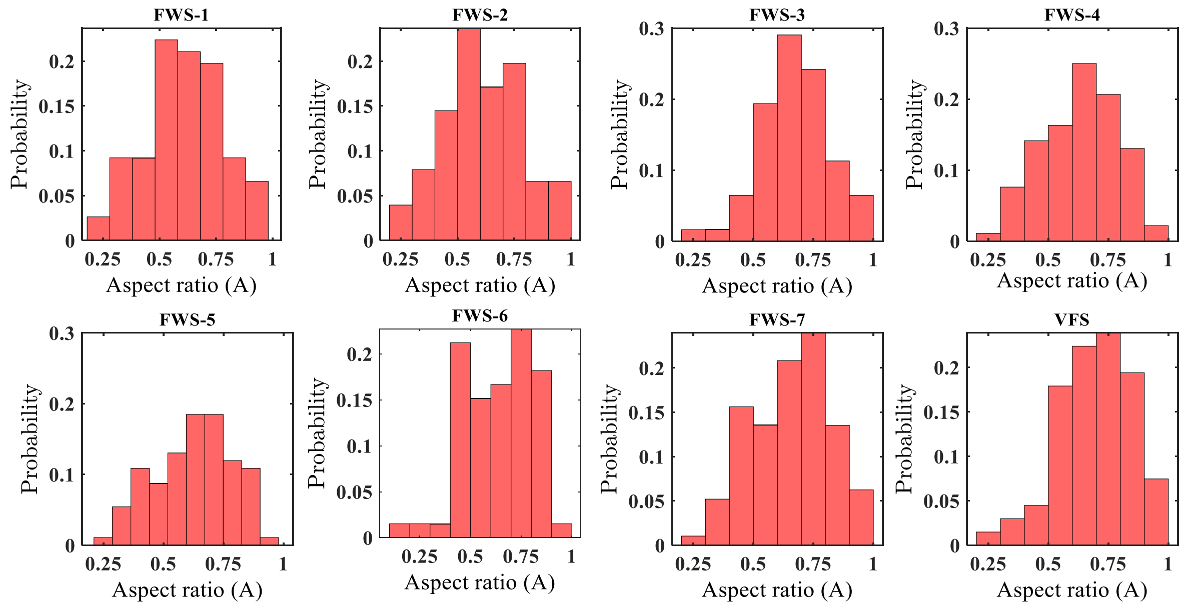


Figure 5. *Aspect ratio histograms of different foundry waste sand*

3.2 Fourier transform infrared spectroscopy (FTIR)

FTIR spectroscopy is a technique used to analyse the chemical composition of a sample by measuring the infrared absorption spectrum of the sample. The absorption spectrum is obtained by exposing the sample to a broad range of infrared wavelengths, and the resulting information is used to identify specific bonds and determine the chemical structure of the molecules in the sample. The samples were pulverised into a fine powder and pallets were prepared with potassium bromide (KBr). The prepared pallets were then placed on the FTIR apparatus, then background corrections were made with the accumulations of 32 scans. The functional groups were identified from the FTIR spectroscopy as shown in Figure 6. It was observed that all the 8 samples have similar peaks, even if they are from the different source. The highest peak broadband was observed between 700 to 1300 cm-1, which indicates tetrahedral carbon-hydrogen (C-H) bonds. The peak broadband was observed from 1300 to 1400 cm-1, which shows that it belongs to (O-H) bonding. The highest peak broadband was observed between 2800 to 3000 cm-1 which shows that the range belongs to carbon-hydrogen (C-H) bonds. Most of the peaks for all the FWS samples were similar to the peaks observed by Carnin et al. (2012).

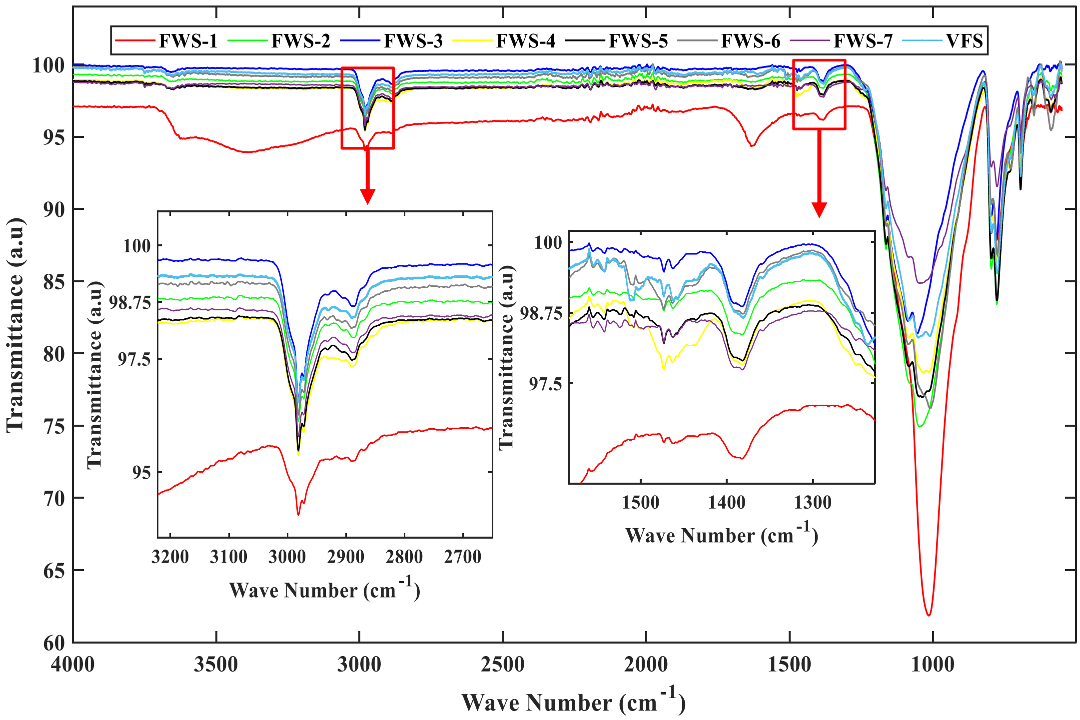


Figure 6. *FTIR spectra of different foundry waste sand*

3.3 Powder X-ray diffraction (XRD)

Powder X-ray diffraction (XRD) is a technique used to analyse the structure of crystalline materials. In the present study, all the samples were grinded into a powder form using mortar and pestle and then placed in an x-ray diffractometer. The 2-theta (2θ) range from 5^0 to 100^0 was used to get the diffraction pattern. From the results, the size and percentage of the crystalline structure were found and are provided in Table.3. The average crystallite size of the FWS samples ranged between 37 nm and 43 nm from Scherrer equation, between 45 nm and 50 nm from modified Scherrer equation, and between 47 nm and 60 nm from Williamson – Hall method. The strain of the FWS varied from $4E^{-04}$ to $6E^{-04}$ and crystallinity percentage varied from 66 % to 84 %. The XRD plots are shown in Figure 7. In the present study, quartz and periclase were observed to be the major constituents in all the FWS samples which is consistent with the data report in the literature (Kumar & Parihar, 2022).

3.4 Toxicity Characteristic Leaching Procedure

The TCLP is a test used to determine whether a material is hazardous according to the regulations of the United States Environmental Protection Agency (EPA). The TCLP test is used to simulate the leaching of hazardous substances from a waste material under conditions similar to those that might occur in a landfill. The TCLP test is an important tool for managing hazardous waste, as it helps to ensure that hazardous materials are properly disposed of and do not pose a risk to the environment or human health. In the present study, US EPA method 1311 was used to get the leaching potential of the FWS samples. The pH of FWS in its natural state and after the addition of HCl was measured to obtain the extraction fluid procedure to be followed for subsequent analysis. The pH values for all the FWS samples were observed to be less than 5 after addition of HCl. Hence the extraction fluid procedure 1 was followed for further testing. For standard extraction solution, the glacial acetic acid and sodium hydroxide solution was diluted by 500ml of water. A sample to extraction fluid ratio of1:20 was maintained. The sample was then kept in a rotary agitator for and a revolution of 30 R.P.M was applied for 18 hours. Finally, the sample was filtered using pressurized vacuum filter. Then the extracted fluid was kept on Inductively coupled plasma- mass spectrometer (ICP-MS) for analysing the leachable heavy metals.

The results obtained from the toxicity characteristic leaching potential analysis of FWS were compared with the Hazardous waste management rules and are given in the Table.5. (Zhang et al., 2014; Alves et al., 2014). In the present study, all the elements were observed to be well within the prescribed limits.

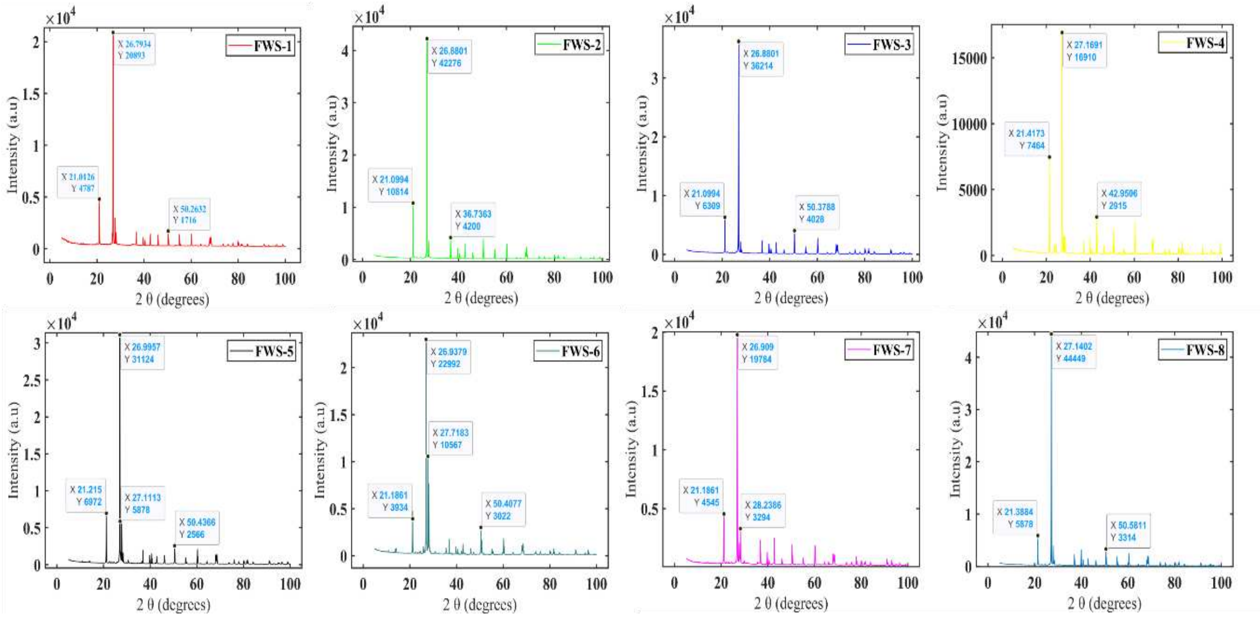


Figure 7. *XRD patterns of different foundry waste sands*

Table 3. *Crystallinity present in FWS*

Sample ID	Crystallite size, d (nm)			Strain	Crystallinity (%)
	Scherrer	Modified Scherrer	Williamson-Hall		
FWS1	37.83	49.71	60.28	0.0006	67.33
FWS2	41.95	50.21	60.28	0.0006	76.22
FWS3	40.45	48.25	55.46	0.0006	84.03
FWS4	39.37	45.9	49.52	0.0004	69.05
FWS5	43.07	45.9	53.33	0.0005	66.35
FWS6	39.09	45.9	53.33	0.0005	66.41
FWS7	34.29	43.67	47.81	0.0004	58.65
VFS	39.87	47.29	55.46	0.0006	71.88

Table 4. *Toxicity characteristic leaching potential test results of FWS*

Element	FWS 1	FWS 2	FWS 3	FWS 4	FWS 5	FWS 6
Cr (mg/L)	0.15	Nil	Nil	Nil	Nil	0.0005
Cd (mg/L)	0.00	0.0003	0.0005	0.0001	0.0003	0.0001
Cu (mg/L)	0.01	0.021	0.044	0.007	0.021	0.011
Al (mg/L)	0.34	0.47	0.144	0.02	0.32	0.155
Zn (mg/L)	0.046	0.072	0.073	0.013	0.118	0.273
Pb (mg/L)	Nil	0.002	0.002	0.0005	0.005	0.002
Ni (mg/L)	0.032	Nil	0.003	Nil	0.01	Nil
Fe (mg/L)	0.302	0.424	0.043	0.0127	0.117	0.167
Ti (mg/L)	0.0128	0.0124	0.004	0.002	0.011	0.005

Cr = Chromium; Cd = Cadmium; Cu = Copper; Al = Aluminium; Zn = Zinc; Pb = Lead; Ni = Nickle; Fe = Iron; Ti = Titanium

***Table 4.** Toxicity characteristic leaching potential test results of FWS (continued)*

Element	FWS 7	VFS	Zhang et al., 2014	Alves et al., 2014	MoEF & CC (mg/L)	US-EPA Regulatory level (mg/L)
Cr (mg/L)	0.0017	0.002	0.01-0.011	0.06	5	5
Cd (mg/L)	0.0001	0.0003	0.0005 -0.005	<0.004	1	1
Cu (mg/L)	0.021	Nil	0.008-0.039	0.04	25	-
Al (mg/L)	0.43	0.22	0.192-1.95	<0.03	-	-
Zn (mg/L)	0.053	0.021	0.22-0.98	1.9	250	-
Pb (mg/L)	Nil	0.0003	0.007-0.03	0.02	5	5
Ni (mg/L)	Nil	Nil	0.002-0.03	0.03	20	-
Fe (mg/L)	0.199	0.103	0.04-4.4	60.7	-	-
Ti (mg/L)	0.004	0.002	-	-	-	-

Cr = Chromium; Cd = Cadmium; Cu = Copper; Al = Aluminium; Zn = Zinc; Pb = Lead; Ni = Nickle; Fe = Iron; Ti = Titanium

4 CONCLUSIONS

The present study focused on investigation of the mineralogical and morphological characterization of seven different source of FWS samples and the following conclusions were made:

- From the physical characterisation of the samples the FWS can be classified as poorly graded sand (SP) and 60 to 70% of the particle sizes ranges between 75 µm to 425 µm.
- The mineralogical composition of FWS from the different source were found using physico chemical methods. The silica (Si), alumina (Al), potassium (K) and iron (Fe) are the dominant elemental compositions available in all the FWS samples.
- From the morphological studies, almost all the seven FWS and the virgin sand are having shape descriptors are having a range of subangular to subrounded.
- The FTIR analysis showed that major peaks lie in C-H and O-H bonding in all the FWS samples. The powder XRD analysis indicates that the crystallinity of FWS lies in the range of 59% to 84%.
- The TCLP tests revealed that the concentration of the heavy metals like chromium, cadmium, zinc, copper, lead, and nickel are within the threshold limits stipulated by the various environmental protection agencies. Hence, the FWS can be a good option for replacement with natural sand or improvement of softer ground and the usage can lead to sustainable geotechnical applications.
- The results presented in this article are from the initial investigations as part of the sustainable re-use of waste materials in geotechnical applications. The detailed analysis including strength, stiffness and hydraulic properties of the different foundry waste materials including their interaction with geosynthetic materials are in progress. The results will be disseminated as and when the testing is completed including a detailed long-term exposure of FWS to geosynthetic materials such as geotextile and geogrids for assessing their suitability as fill material.

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REFERENCES

Abichou, T.H., Benson, C.H., 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, Wis., USA.

Altuhafi, F., O Sullivan, C., & Cavarretta, I. (2013). Analysis of an image-based method to quantify the size and shape of sand particles. Journal of Geotechnical and Geoenvironmental Engineering, 139(8), 1290-1307.

Alves, B. S., Dungan, R. S., Carnin, R. L., Galvez, R., & de Carvalho Pinto, C. R. (2014). Metals in waste foundry sands and an evaluation of their leaching and transport to groundwater. Water, Air, & Soil Pollution, 225, 1-11.

Bhardwaj, B., & Kumar, P. (2017). Waste foundry sand in concrete: A review. Construction and building materials, 156, 661-674.

Carnin, R. L., Folgueras, M. V., Luvizão, R. R., Correia, S. L., da Cunha, C. J., & Dungan, R. S. (2012). Use of an integrated approach to characterize the physicochemical properties of foundry green sands. Thermochimica acta, 543, 150-155.

Cavarretta, I., Coop, M., & O SULLIVAN, C. (2010). The influence of particle characteristics on the behaviour of coarse-grained soils. Géotechnique, 60(6), 413-423.

Cioli, F., Abbà, A., Alias, C., & Sorlini, S. (2022). Reuse or Disposal of Waste Foundry Sand: An Insight into Environmental Aspects. Applied Sciences, 12(13), 6420.

Dyer, P. P., & de Lima, M. G. (2022). Waste foundry sand in hot mix asphalt: A review. Construction and Building Materials, 359, 129342.

Guney, Y., Aydilek, A. H., & Demirkan, M. M. (2006). Geoenvironmental behavior of foundry sand amended mixtures for highway subbases. Waste management, 26(9), 932-945.

Gupta, G., Datta, M., Ramana, G. V., & Alappat, B. J. (2021). MSW incineration bottom ash (MIBA) as a substitute to conventional materials in geotechnical applications: A characterization study from India and comparison with literature. Construction and Building Materials, 308, 124925.

Heidemann, M., Nierwinski, H. P., Hastenpflug, D., Barra, B. S., & Perez, Y. G. (2021). Geotechnical behavior of a compacted waste foundry sand. Construction and Building Materials, 277, 122267.

Hryciw, Roman D., Junxing Zheng, and Kristen Shetler. (2016). Particle roundness and sphericity from images of assemblies by chart estimates and computer methods. Journal of Geotechnical and Geoenvironmental Engineering, 142.9 (2016): 04016038.

Kalyan, N.S.S.P., Kandasami, R.K. (2021) Computationally efficient approach to quantify 2D particle morphological descriptors. In EPJ Web of Conferences, EDP Sciences, vol 249, p 05002.

Kumar, A., & Parihar, A. (2022). State-of-the-Art Review on Sustainability in Geotechnical Applications of Waste Foundry Sand. Indian Geotechnical Journal, 52(2), 416-436.

MoEF&CC (2016) The Hazardous Waste Management and Handling Rules, The Ministry of Environment, Forests and Climate Change, New Delhi, India.

Mitchell, J. K. & Soga, K. (2005). Fundamentals of soil behavior, 3rd edition. New York, USA: Wiley.

Pai, R. R., Bakare, M. D., Patel, S., & Shahu, J. T. (2021). Structural evaluation of flexible pavement constructed with steel slag–fly ash–lime mix in the base layer. Journal of Materials in Civil Engineering, 33(6), 04021097.

Powers, M. C. (1953). A new roundness scale for sedimentary particles. J.Sediment. Res.,10.1306/D4269567-2B26-11D7-8648000102C1865D,117–119.Riley, N. A.

Rodriguez, J., Edeskär, T., & Knutsson, S. (2013). Particle shape quantities and measurement techniques: a review. The Electronic journal of geotechnical engineering, 18, 169-198.

Siddique, R., Kaur, G., & Rajor, A. (2010). Waste foundry sand and its leachate characteristics. Resources, Conservation and Recycling, 54(12), 1027-1036.

U.S. EPA. Test Methods for Evaluating Solid Waste, Physical/ Chemical Methods, SW-846 On-Line; http://www.epa.gov/ epaoswer/hazwaste/test/main.htm

Zhang, H., Su, L., Li, X., Zuo, J., Liu, G., & Wang, Y. (2014). Evaluation of soil microbial toxicity of waste foundry sand for soil-related reuse. Frontiers of Environmental Science & Engineering, 8, 89-98.