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A Critical Review on Potential Use of Waste Foundry Sand in Geotechnical and Pavement Applications

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Abstract. In recent years, industrial recycled and waste materials have been utilized considerably in various civil engineering applications. To aid the metal casting process, metal foundries throughout the world use about 105 million tons of foundry sand annually. When the sand becomes unfit for molding, it is discarded in the landfill as waste foundry sand (WFS). India produces around 3 million tons of foundry sand annually. US Environmental protection Agency (EPA) has estimated that applications of WFS in construction works could prevent 20,000 tons of CO_2 emissions and save 200 billion BTU of energy. Sustainable reuse of WFS can furnish an economical and environmentally beneficial solution to conserve landfills and virgin sands. This paper presents a state-of-the-art review of the reuse potentials and engineering properties of WFS as a suitable material in various geotechnical and pavement applications. This study discusses available information on WFS from a geotechnical perspective. Evaluation and characterization of geotechnical behavior and environmental properties of WFS may necessitate its effective utilization in the construction industry. Some existing recovery processes of WFS and its uses are also discussed. Large-scale application of WFS in various civil engineering works may significantly reduce the quantity of waste generated in the state.

Keywords: Foundry sand; Geotechnical behavior; Pavements; Sustainable construction.

1 Introduction

As reported by the Foundry market in India (2018-2023), globally, India is the second largest producer of metal castings. Around 40% of castings produced in India are consumed by the Automobile sector. As of 2018, the contribution of aluminum castings in the country is around 15% of total casting production. As a consequence of the shift in demand from iron to lighter casting materials for manufacturing fuel-efficient automobiles and electronic vehicles (EVs), there will be a considerable increase in the share of iron by the end of 2023. Expansion of infrastructure by the government due to its focus on “Make in India”, “Ease of Doing Business” also easing FDI norms to promote investments in manufacturing is expected to generate demand for a wide variety of machinery and equipment, which will in-turn create fresh demand for metal casting. Approximately, 4500 units produce metals in India [1]. Metal castings in India are expected to expand at a compound annual growth role (CAGR) of approximately 12.7% from 2018 until 2023 [1]. The increasing demand for metals in forthcoming years will intensify the production of metal castings, which leads to an increase in industrial waste production like foundry sand and foundry slag. These waste products named Waste foundry sand (WFS) that are disposed to landfills after repeated utilization may impose several environmental issues due to their composition. Sustainable reuse of this large mass of waste products will meet the demand for green industrialization in the construction industry. The present study discusses the state-of-art review on the potential reuse of WFS in various civil engineering applications, especially, geotechnical and pavement applications.

2 The Foundry Sand

2.1 Production of Foundry sand

Foundry industries producing iron and steel castings (ferrous family) and aluminum, bronze, and copper castings (non-ferrous family) use a large volume of high-quality size-specific silica sand as base sand for casting purposes [2]. A uniform mixture of silica sand (75 – 90%), bentonite (4 – 16%), coal dust (2 – 10%), and water (4 – 5% of the total quantity of silica sand) are used in the molding process to get the required shape. Silica sand in the mixture provides structure to the mold, coal dust (also known as black mineral) increases the refractory of the sand and bentonite acts as a binder agent. Water is added to activate the binder transformation in gel to achieve appreciable cohesion to the mold [2,3].

Apart from Silica sand, various other types of base sand with high thermal properties like Chromite sand, Zircon sand, Olivine sand, and Chamotte sand are used in foundry industries. Considering availability and the cost of base sand, 90% of the metal casting industries use Silica sand as base sand. Similarly, binders other than bentonite such as Olivine, Magnetite, iron oxide, sea-coal, phenol resin, etc., are used with the base sand [7].

In the process of metal castings, after demolding of casting by shakeout, the molding sand is recycled and reused. After multiple reuses, molded sand is termed as a waste product and discarded at the landfill. This waste product with high silica content, both from ferrous and nonferrous casting industries is known as waste foundry sand (WFS). Two classified types of foundry sand namely “Green sand” and “Chemically bonded sand”. “Green sand” also called “Clay – bonded sand” of grey or black color with 75 – 90% silica content and “Chemically bonded sand” also called “Resin sand” of white or off-white color with 90 – 95% silica content are produced by casting industries [8].

2.2 Recovery of Foundry sand

Reuse of molding and core sand after demolding necessitates the recycling of the used sand. The usual recycling process adopted for second fusion iron metal is using mulling and sieving operations followed by the addition of the required amount of bentonite, coal, and water to obtain the essential mix. All around the world, there are many regeneration plants to recover the spent foundry sand.

Mechanical and thermal attrition are the two essential processes to recover molding sand. Thermal regeneration, wet regeneration, and dry attrition are the three processes that are attempted to recover the core and molding sand. The sand that is recovered will be used for mold making but cannot be used for the core-making process [2].

A schematic diagram representing the flow of foundry sand is shown in Fig. 1 [3,4].

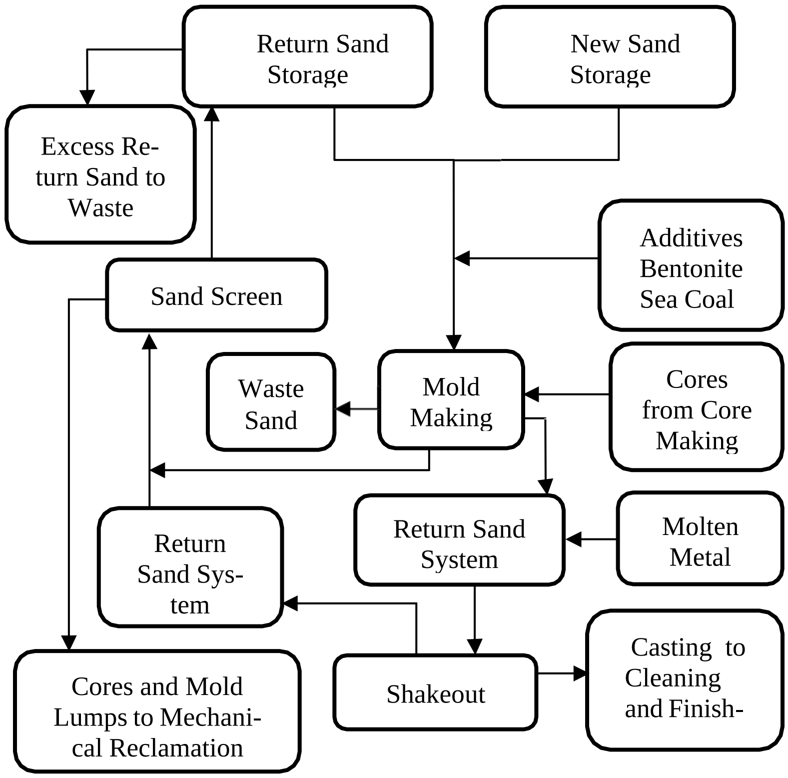

Fig 1. A schematic of the flow of sands through a typical foundry, [3,4]

Khan (2020) developed a laboratory method for reclaiming the spent foundry sand using a mechanical attrition device. This device can reclaim the spent sand through attrition followed by the sieving process. It removes the coating of the binder from foundry sand [5]. The details of the reclamation device and the corresponding operating conditions are given in Fig. 2 and Table 1, respectively. Fines generated during this process are around 10 – 15%. The extent of fines generation varies from sand to sand. The fines collected during this process are <50 μm. Disposal of the collected fines is done carefully to avoid exposure/pollution. As these fines do not provide strength to the mold, these are not reused for molding purposes, but these can be utilized in the construction industry such as civil construction, roads, ceramics, etc. [6].

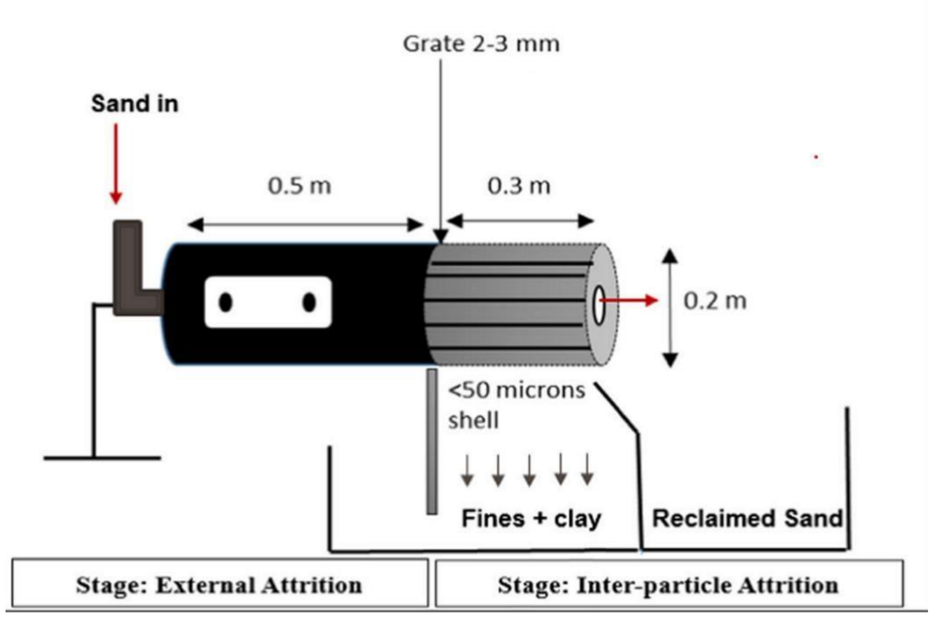

Fig 2. Reclamation device for spent foundry sand [8]

Table 1. Parameters for operating condition of reclamation device [8]

Parameter	Values
MOC of balls	Agate (Cryptocrystalline silica) (Hardness: 7-8 Mohs)
Ball charge (%)	20-30
Sand charge (%)	30
Speed (rpm)	10-50
Ball Weight (g)	30-40
Ball Diameter (mm)	<40
Attrition time (min.)	25

3 State-of-the-art review on Waste Foundry Sand

3.1 Mineralogical Composition

Waste Foundry Sands (WFS) are finer materials consisting of different chemical compositions. X-ray Diffraction (XRD) is performed to know the major and minor minerals present in WFS. Major minerals present are Silicon dioxide (SiO_2), Iron oxides (Fe_2O_3), and Alumina oxide (Al_2O_3). Further X-ray fluorescence (XRF) and SEM-EDS tests were performed to know the minor minerals and shape of the particles present in WFS. Other trace elements include oxides of Ca, Mg, Na, K, S, Ti, Pb, Cr, Cd, Zn, and Ni. Table 2 gives the chemical composition of WFS reported in the literature.

Table 2. Chemical composition of WFS from various works of literature.

Composition	Values (%)					
	[5]	[6]	[9]	[10]	[11]	[19]
Silica (SiO_2)	73.912	78.81	98	87.91	62.5	84.145
Aluminum (Al_2O_3)	6.407	6.32	0.8	4.70	13.1	11.817
Iron (Fe_2O_3)	11.395	4.83	0.25	0.94	4.1	1.533
Potassium (K_2O)	1.083	0.10	0.04	0.25	4.2	0.287
Calcium (CaO)	1.207	1.88	0.035	0.14	1.9	1.507
Sodium (Na_2O)	0.869	0.05	-	0.19	0.10	-
Magnesium (MgO)	1.488	1.95	0.023	0.30	0.5	-
Manganese (MnO)	0.213	-	-	-	4.4	-
Nickel	-	-	0.004	-	-	-
Sulphur (SO_3)	1.462	0.05	-	0.09	-	0.453
Chromium	-	-	0.003	-	-	-
Lead	-	-	0.003	-	-	-
Zinc	-	-	0.003	-	-	-
Copper	-	-	0.002	-	-	-
Cadmium	-	-	0.001	-	-	-
Titanium (TiO_2)	0.625	-	-	0.15	0.8	0.257
Trace element	-	-	0.836	-	-	-
LOI	-	2.15	-	5.15	-	-

3.2 Geotechnical properties of WFS

Geotechnical properties like grain size distribution, permeability, compaction, direct shear, UCS, CBR, and swelling tests were performed to know its geotechnical potential. pH and leachability tests using TCLP experiments were performed by various research-ers to know the toxicity characteristics of heavy metals present in WFS for its potentialuse in various geotechnical and pavement applications. Table 3 shows the results of the physical properties of foundry sand, whereas Table 4 shows the results of the leaching test of WFS reported in the literature.

Table 3. Geotechnical Properties as reported by various works of literature

Properties	[9]	[12]	[18]	[19]
G	2.45	2.62	2.61	2.59

Classification	SM	SP	SW	SP
C_u	5.5	1.7	3.57	2.06
C_c	-	3.2	1.65	0.92
Fine (%)	24	12	12	2
OMC (%)	3.25	16	11.5	12.5
MDD (g/cc)	-	1.67	1.753	1.748
CBR (%)	-	-	12	10.9
UCS (kPa)	-	-	47-97	
Permeability (m/sec)	-	10^{-3}	-	5.2×10^{-8}
Plasticity	-	-	Non-plastic	-
Φ'	-	31.1	32.5-29.2	-
c'(kPa)	-	8.6	18-31	-

Table 4. Summary of heavy metals concentration in leaching analysis

Parameters	Value (mg/l)					
	[5]	[12]	[13]	[14]	[15]	[19]
Ag	-	-	<0.005	<0.01	5.0	0.0027
As	<0.5	-	<0.01	<0.001	5	0.023
Ba	-	0.133	0.22	1.65	100	0.0712
Cd	<0.5	-	<0.004	<0.001	1.0	0.007
Cr	<0.5	<0.1	0.06	0.680	5.0	0.078
Cu	<0.5	<0.1	0.04	-	-	-
Fe	<0.5	-	60.7	-	-	-
Hg	<0.5	<0.001	<0.006	0.00039	0.2	-
Mg	2.54	-	7.7	-	-	-
Mn	-	-	0.97	-	-	-
Ni	<0.5	<0.1	0.03	-	-	-
Pb	<0.5	<0.1	0.02	-	5.0	0.009
Se	-	<0.05	<0.009	<0.008	1.0	0.013
Zn	<0.5	1.067	1.9	-	-	-

3.3 Applications of WFS

Foundry sand that is produced in a massive amount from the foundry industries needs special attention to conserve landfills as well as to avoid negative impacts on the environment. Green construction technology is the need of the hour in the construction industry to minimize the use of raw materials like fine aggregates (natural sand). Due to the scarce availability of natural sand, the replacement of fine aggregates with some percentage of waste materials will be useful in sustainable development.

Waste foundry sand can be effectively utilized in geotechnical and pavement applications like flowable fills, embankment construction, retaining walls, hydraulic barriers, soil stabilization techniques, subgrade, and subbase construction, etc. The studies carried out by various researchers on WFS are discussed below.

Embankment. Embankment and structural fill need a large volume of earthen material as a compacted foundation in place to transfer the desired load. Roadway applications, in particular fill for abutments or slabs, filling of trenches, or backfill for retaining walls/structures and other excavations need a stable and strong structural fill. To raise the elevation of roadways or railways above the existing surrounding ground level in order to provide a strong foundation and to facilitate proper drainage, desired embankment fill is required. American foundry society (AFS), FHWA provides guidelines and specifications to choose the proper material to serve this purpose [16]. Characterizing of engineering and index properties of the chosen material is required to understand the behavior of the material at the site [17].

Heidemann (2021) investigated the behavior of WFS with three compaction efforts of 600 kJ/m^3, 1260 kJ/m^3, and 2700 kJ/m^3 and obtained an increase in internal friction angle and cohesion. An increase in unconfined compression strength (ranging from 47kPa to 97 kPa) was observed with an increase in compaction effort. Due to matric suc-tion, a remarkable increase in UCS (ranging from 2,550 kPa to 3,356 kPa) of the air- dried specimen that are tested after 14 days was also obtained. However, this increase in strength may even reach 50,000 kPa in drier conditions due to suction. But this strength will be lost with the increase in moisture content [18].

Arulrajah (2017) analyzed the behavior of WFS to compare it with recycled glass (RG) for applications in embankment or retaining walls and pipe bedding construction. The CBR values falling within the limits of local standards showed the viability of WFS in road construction. Typical embankment construction and flow of water through the filling material when WFS used as non-structural fill is shown in Fig. 2 [19,20].

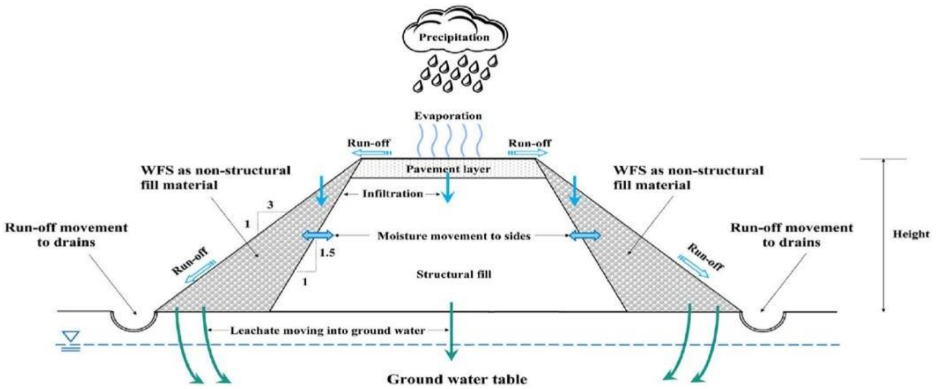

Fig 2. Water flow balance chart for WFS as fill material in road embankments [19]

Iqbal (2019) found that an optimum replacement of natural sand by 6% WFS meets the CBR, specific gravity, permeability, and compaction criteria wrt. embankment and structural fill material. [21].

Pavement layers. Stabilized WFS mixed with crushed rock showed great durability and strength potential under frost heave and resistance to freezing-thawing cycles with less frost susceptibility in comparison with virgin WFS without coarser aggregates. Zhang (2021) also reported a reduction in cost and CO_2 emission by up to 50% and 46% compared to the reference structure [22].

The mechanical and microstructural investigations of Dyer (2021) by replacement of fine aggregate by WFS by weight with a dense gradation in hot mix asphalt pavement (HMA) proved to have technical viability to use as the surface course layer in asphalt pavement. The asphalt binder provided safety to the environment by encapsulating WFS which eliminated the presence of pathogenic substances [23].

An improved moisture sensitivity was obtained in the pavement of HMA containing WFS with cement filler type. Joni (2016) also observed improvement in mechanical properties of HMA containing used WFS as fine aggregate retained on a 75-micron sieve [24].

Bharadwaj and Sharma (2022) obtained the maximum reduction in the thickness of pavement layers and construction cost of the flexible pavement with a combination of 10% molasses, 20% WFS, and 3% lime used in subgrade construction. IITPAVE software showed reduced layer thickness of all the combinations of molasses, WFS, and lime for various values of commercial vehicles/day (1000, 2000, and 5000) in designing the thickness of flexible pavements [25].

Klinsky (2016) obtained similar results as that of lateritic sandy soil for CBR and mini CBR with 60% WFS content. A slight variation in Resilient modulus (MR) was observed, but the WFS-lateritic soil mixture presented appropriate MR values for its use in sub-base courses [26].

Geotextile, geonets, geogrids, geomembranes, and geocomposites – the fabrics produced from polymer fibers are the synthetic fibers included in geosynthetics. These geosynthetics are widely used in retaining walls, shallow foundations, embankments, roadways, railways, slopes, and many other applications as they are functioning as separators of two dissimilar materials, filters, drainage providers, and also reinforcements [27]. Goodhue (2010), performed small-scale shear tests, large-scale multistage interface shear tests, and pull-out tests using WFS in combination with different geosynthetics such as geotextile, geogrid, and geomembrane. The friction angle ranged between 39˚ and 43˚, cohesion between 17 and 29 kPa with typical interface friction angles between 25˚ to 35˚ along with efficiency between 0.5 – 0.9, and the interaction coefficient from the pull-out test ranging between 0.2 – 1.7 indicating the efficient usage of foundry sand in geotechnical construction [28].

Backfill. ACI 2291-99 defines flowable fills or controlled low strength (CLSM) as “a mixture of soil, fly ash, cement, some amount of water with some addition of admixtures that hardens into material with higher strength than soil but less than 8.3 MPa” [29]. The improved construction safety, easy delivery, and placing, low shrinkage and compressibility, strength and durability, less time for hardening, easy excavatable at any stage, and no requirement for compaction are some of the advantages of flowable fills. Flowable fills are commonly used as backfill behind retaining walls [30].

Bhatt and Lovell (1996) partially substituted WFS as a fine aggregate instead of sand in flowable fills. 90 days results of the compression test indicated the maximum rise of 25 – 30% long-term strength as compared to 28-day strength. Hardened flowable fill showed less permeability of about 10^{-6} cm/sec. Low chances of corrosion are indicated by the pH of the hardened fill [31].

Jeffrey (2004), observed the increase in strength and flow behavior of flowable fills when WFS with bentonite content >6% is used as a fine aggregate. The flow characteristics revealed that an increase in bentonite content increases the amount of water content required for the mixture. The advantages obtained from the study include: flow loss observed due to the presence of cementitious fly ash can be reduced by adding foundry sand. A lower gain of long-term strength was obtained [32].

Trejo (2004), reported that the waste foundry sand from ferrous prominent industries has potential for environmental impacts by leaching of heavy metals present in it [33]. As recommended by Environmental Protection Agency (EPA), non-ferrous WFS cannot be used for CLSM due to concern of potential leaching of phenols and also heavy metals like lead, copper, zinc, and cadmium [34].

Department of transportation (DOTs) recommended specifications related to WFS used in flowable fill applications include: concrete with 10-15% WFS replacement has the highest strength. Increasing WFS content reduces the workability, hence there is a requirement for an increase in superplasticizer. The combination of WFS with natural sand helps to achieve desirable performance. Increasing WFS by up to 10% reduces sulphate attack, a 30% increase in the WFS increases permeability, and WFS will also enhance the chloride penetration resistance [35].

Karnamprabhakara (2022), observed higher axial and transverse pull-out resistance with the geogrid of higher tensile strength having a higher opening area in the interaction of WFS with geogrid. Authors also formulated empirical equations to estimate axial and transverse pull-out resistance of geogrid for two pull-out displacements [36].

Landfills. International standards recommend the use of landfill cover layers to isolate the solid waste and to resist the penetration of leachate from this waste to the environment by recommending landfill cover layers having less permeability (approximately 10^{-6} cm/s < K > 10^{-9} cm/s) [37,38]. Domingues (2015), utilized WFS in the cover layers of solid waste landfills and observed that 70% of laterite soil can be replaced by WFS in the landfill cover layers [39]. An improved lifetime of landfills was also observed with this replacement [40].

WFS, fly ash (FA), expanded polystyrene (EPS), Portland cement, and water called a WFS-FA-EPS mixture enhanced frost heave mitigation with an increase in cement content up to 4%, EPS content up to 1%, and a decrease in water content up to 20 – 25%, by mass of WFS, in earth fills compared to common earth fill. Deng (2010), observed a decrease in the thermal conductivity and buffer freezing expansion of the mixture when anti-frost geomaterial which blends WFS-FA-EPS mixture in proportion is used in earth fill [41].

4 CONCLUSION

Waste foundry sand is utilized in applications such as flowable fill, landfill layers, embankment and structural fill, and other geotechnical and pavement applications. Waste foundry sand is gaining more attention due to its compatibility with other materials like fly ash, laterite soil, molasses, lime, and geosynthetics. The replacement of WFS containing 6% bentonite content with fly ash incorporated in flowable fills proved advantageous. The 70% replacement of WFS with laterite soil improved the strength of landfill covers. Soil stabilized with the combination of WFS (20%), molasses (10%), and lime (3%) gave the best way to minimize differential free swelling and pavement thickness as well as to enhance CBR. Industrial waste utilized in various applications helps to conserve natural materials. The interaction of WFS with geosynthetics gave similar results to that of common materials used in the application. The best use of WFS in subbase and base courses of pavement applications proved cost-effective. The leachate characteristics of WFS from the ferrous family are reported to be non-toxic.

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