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TransFIRe Case Study: Spent Foundry Sand Technical Literature Review

24th March 2023

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EPSRC Project Reference: EP/V054627/1

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1. Introduction

In accordance with TransFIRe Work Stream 2, “Where there's muck, there's brass - creating new materials and process opportunities” and its associated Case Study focussing on Spent Foundry Sand, this report provides a literature review of technical aspects relevant to potential beneficial re-use applications of Spent Foundry Sand (SFS) arising from UK metals foundries, in the Foundation Industries and beyond. The primary purpose of this technical literature review is to identify possible technical opportunities for re-using SFS, including applications such as ceramics, glass, cement, fillers in concrete and asphalt; and several other potential applications. Re-use / repurposing of these wastes could not only divert them from landfills but also potentially generate additional economic opportunities by creating new, low-carbon alternative raw materials, new processes and new supply chains.

2. Background

A foundry manufacturing facility manufactures metal castings by pouring molten metal into a premade mould and solidifying the resulting casting. Spent foundry sand* (SFS) is a discarded material coming from ferrous (iron and steel) and nonferrous (copper, aluminium, and brass) metal-casting industry to create molds and cores.[1] The physical and chemical properties of spent foundry sands depend strongly on the casting processes and the industrial sector(s) from which they are derived [2].

Foundries acquire high-quality silica sands with specified particle sizes for moulding and casting operations. The requirement is principally for clay-free (washed) sands, which are rich in silica, SiO_2. They should also have a uniform (narrow) size distribution and grains with generally high sphericity.[3] For example, for the sand provided by Tarmac, the silica content is in excess of 96% and the grains are predominantly sub-rounded .[4] Each foundry may have its own requirements for foundry sand, the supplier provides abundant technical information for the sand, and those parameters were measured according to British Standards (such as Tarmac WR440 sand, which is silica sand from Cheshire[4] and its typical aggregate properties were measured according to BS EN 1097-6: 2000 , BS EN 1744-1:2009, BS EN 1097-3: 1998, BS EN 196-21: 1992, BS 1377-3: 1990 and BS EN 1367-4: 2008). A binding agent, such as clay (usually bentonite) or a chemical (e.g., resin), is added to the sand and the moulds produced.[3] After casting, solidification and cooling of the metal, the moulds or cores are dismantled to recover the metal parts in a process called knock[1] out or shake-out, depending on the method

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*****: *Interchangeable names for spent foundry sand (SFS), such as waste foundry sand (WFS) or used foundry sand (UFS) exist. The term spent foundry sand (SFS) has been used throughout this report.*

used and physical size of mould. The moulds are completely removed. Moulding sands are usually recycled and used several times in casting processes. The recycling process uses screening systems and magnetic separators to recover valuable sand from other wastes and separate particles of varied sizes[5]. Although foundry sand can be successfully recycled and used numerous times, the sand grains eventually degrade and their ability to bind with other substances decreases. Meanwhile, this also generates dust due to heat and mechanical wear. Therefore, new sand must be continually fed into the system to maintain adequate tolerances and prevent casting flaws[6]. The fine dust and unusable sand components must be separated and removed from the process. Consequently, SFS is continually generated.

When the foundry sand becomes unfit for use in the manufacturing process, it is generally disposed of at foundry landfills or off-site municipal landfills.[2] Approximately 1 tonne of foundry sand is utilised for every 1 tonne of iron or steel casting produced.[5] This sand can then be re-used in the foundry with a small percentage needing to be replaced (due to process and recycling losses as described above). Suppliers to the automotive sector and manufacturers of its components are often the largest producers of spent foundry sand.[5]

The ferrous foundries (grey iron, ductile iron and steel) use the most foundry sand, and aluminium, copper based and magnesium use the rest. In the UK, over 450 foundries produce 530,000 tonnes of castings in all metals with an annual value of £2.2 billion.[7] They generated over one million tonnes of spent foundry sand annually in 2013 [7], mainly in the Midlands, South and West Yorkshire [8]. Foundry sand is also generated in Lancashire, the North East and Scotland [9]. This data was re-cited in 2019 by Maria *et al.* [10]. According to the statistics from our industrial partner, Cast Metals Federation (CMF), the mass of spent foundry sand generated in the UK was around 200,000 tonnes per annum in 2017/18, and this figure has not changed significantly to date (based on information supplied by the Cast Metals Federation).

Foundry sand is typically recycled and used multiple times within the foundry before it becomes waste. However, less than 15% to 28% of the 6 to 10 million tonnes of SFS produced annually in the USA were recycled in 2015 [11]. Unfortunately, we did not find similar records in the literature for foundries in the UK. In 2017, the expense to the UK foundry industry of purchasing new sand and subsequently disposing of SFS in landfills was significant (much more so now that the UK landfill tax has been implemented: £84.40 per tonne for active waste and £2.65 per tonne for non-active waste) [10], which affects the profitability of foundries in addition to creating a significant environmental burden. For comparison and trend estimation, UK landfill costs in April 2022 were £98.60 per tonne for active waste and £3.15 per tonne for inert waste. This, coupled with increasing transport costs due to fuel price increases; costs of being registered with the Environment Agency (EA) as waste producers; and associated administrative work, all increase financial pressures on UK foundries. There is also the CO_2 burden of quarrying and transporting foundry sand to UK foundries. This has, to our knowledge, not yet been quantified but can be expected to be substantial. Furthermore, many landfill sites are distant from foundries with high inherent costs due to transport and further environmental impact, including transport-related CO_2. Therefore, identifying opportunities to reduce, reuse or repurpose SFS is crucial, from the perspectives of sustainable raw materials use, reduction of CO_2 emissions, and reduction of financial burden on foundries.

3. Foundry sand

3.1 Types of foundry sand

There are two main types of foundry sand are used by foundries: one is greensand, which uses clay as the binder material, constituting about 90% of casting volume.[12] The other is chemically bonded sand, which uses polymers to bind the sand grains together (Table 3.1). Chemically bonded sand is composed of silica sand and catalyst-activated chemical binders. They are widely used in core fabrication, where high strengths are required to withstand the heat of molten metal, but they are also utilised in mould fabrication. The chemicals and silica sand are thoroughly combined; a catalyst commences curing and hardening of the bulk.[13–15]

Greensand consists of[16–18]:

- 85-95% high-quality silica sand.
- 4-10% bentonite clay as a binder that passes a 75 µm sieve (mesh size # 200, ASTM C136-06 Standard Test Method for Sieve Analysis of Fine and Coarse Aggregate) and adheres the body together when mixed with water.
- 2-10% carbonaceous additive, added to improve the casting surface finish.
- 2-5% water for plasticity adjustment.

Greensand also contains traces of chemicals such as MgO, K_2O, and TiO_2. Due to its carbon content, greensand has a black or sometimes grey colour.[18]

Chemically bonded sand consists of 93%-99% high-quality silica sand and 1%–3% chemical binder. [16–18] Although some systems employ inorganic binders such as sodium silicate, [16–18] most systems use organic binders such as phenolic urethanes (phenolic resin), epoxy resins, and furfuryl alcohol.[19]

Table 3.1 Types of foundry sand[2, 16–18]

Sand Type	**Binder**	**Additive**
Greensand	Bentonite clay	Carbonaceous material, water
Chemically bonded sand	Phenolic urethanes (phenolic resin), epoxy resins, furfuryl alcohol	-

According to previous research [20], chemically bonded SFS usually does not contain aromatic compounds but contains but aliphatic compounds such as formaldehyde, that are slightly soluble in water through solvent extraction tests for identifying organic substances. The colour of chemically bonded sand is typically a medium tan or off-white colour [21]. Binder systems associated with foundry sands are summarised in Table 3.2. Alkyd urethane was common in the 1970's and there was an alkyd oil reacted with an di-methyl isocyanate. Ciba Geigy in the 1970's sold the binder, which was superseded by Pep-Set and and Cold Box. Work was conducted recently where the pt 1 resin was replaced using a PF resin to one based on Lignite. American Colloid was also on the market a few years ago but again provided no real advantage. While it is a binder, it is no longer commercially used, according to CMF.

Table 3.2 Binder systems associated with foundry sands [22]

Binder system	Binder components	Sand (wt%)	Binder (wt%)
Alkyd urethane	Linseed oil-based or or synthetically produced alkyd urethane.* Some proprietary binder components contain Pb and Co octanoates to enhance curing velocity	98.0–99.2	0.8–2.0
Phenolic	Phenolic containing resins included resole and furan. Resoles art prepared by a reaction of excess formaldehyde with phenol and the addition of a base catalyst. Furan is a furfuryl alcohol-based resin made with an acid catalyst and either phenol–formaldehyde or other chemical additives depending on the formula	98.5–98.8	1.2–1.5
Shell	Phenol–formaldehyde-based resin consisting of Novolac oligomers that cross-polymerise when heated in the presence of hexamethylenetetramine	97.0–98.0	2.0–3.0
Greensand	A mixture of sodium and/or calcium bentonite is used as the binder, but additional additives include bituminous coal, cellulose, and water	85.0–90.0	10.0–15.0
Natural binders	Aqueous emulsion with a mixture of soybean oil, polysaccharides, reducing sugars, and water	97.0	3.0

3.2 Spent foundry sand (SFS) properties

The physical, chemical, and mechanical properties of SFS strictly depend on the type of binder systems used and the specific process [23]. Typically, there is some variation in the chemical composition of foundry sand from foundry to foundry.

3.2.1 Chemical properties

Depending upon the type of metal, type of binder, and combustible used, the chemical composition of SFS may vary and further influence its performance. Most of the past research focused on the properties of blends in which SFS was used as a secondary component rather than considering the sole properties of SFS[24]. Specifically, waste greensand is rich in silica and coated with a thin film of burnt carbon, dust, and a residual binder such as bentonite, coal/coke, chemicals, or resins. In addition, since silica is hydrophilic, it can attract water to its surface [25] so the moisture in the SFS also needs attention. Generally, SFS's silica content (approximately 70 to 88 wt% SiO_2 from Table 3.3) is lower than regular sand because of additives [26]. As reported by various researchers, the chemical compositions of SFS, [7 26 27 28 13 29 30], are given in Table 3.3. The SFS provided by Khatib *et al.* [7] was obtained from a foundry in the West Midlands, UK.

Table 3.3 SFS chemical compositions (in wt%)

Constituents	American Foundrymen's Society [26]	Etxeberria et al. [28]	Sahmaran et al. [13]	Basar et al. [26]	Singh and Siddique [29]	Prabhu et al. [26]	Thaarrini et al. [30]	Khatib et al.[7]
SiO_2	87.91	84.90	76.0	81.85	83.8	87.48	83.93	97.91
Al_2O_3	4.70	5.21	4.45	10.41	0.81	4.93	0.021	4.7
Fe_2O_3	0.94	3.32	5.06	1.82	5.39	1.31	0.950	0.94
CaO	0.14	0.58	3.56	1.21	1.42	0.22	1.03	0.14
MgO	0.30	0.67	1.98	1.97	0.86	0.18	1.77	0.3
SO_3	0.09	0.29	–	0.84	0.21	0.07	0.057	0.09
MnO	–	0.08	0.46	–	0.047	–	–	
TiO_2	0.15	0.19	0.17	–	0.22	–	–	
K_2O	0.25	0.97	1.20	0.494	1.14	–	–	0.25
P_2O_5	–	0.05	0.04	–	–	–	–	
Na_2O	0.19	0.50	0.38	0.764	0.87	–	–	0.19
LOI	5.15	2.87	5.85	6.93	–	5.81	2.19	5.15

There are concerns that SFSs may include metals that, if leached, might be hazardous to human and animal health if found at high environmental concentrations. This is one potential barrier to SFSs being valued[22]. Those metallic elements typically occurring in foundry sand include Ag, Al, Ba, Be, Cd, Co, Cr, Cu, Fe, Li, Mg, Mn, Mo, Ni, Pb, Sb, Ti, Te, Tl, V, Zn and Zr. [22, 31] Specifically, high concentrations of Zr can arise in some samples due to the paints used in the moulds; [22, 31] Zn is commonly elevated in sands used in the presence of poured metals such as bronze; [22, 31] Ba arises in the ductile iron foundry process due to the additives added to greensand. [22,32] Pb occurs from either the use of this metal in alkyd urethane (AU) resin [32] [1] or bronze casting. Meanwhile, the Co concentration is also high in some SFS when AU binder was applied to the foundry sand [22]. However, the fact that Al, Ba, Fe, Mg, Mn, and Zn concentrations are elevated in greensands is of only limited environmental concern, as these metals are naturally available in high concentrations in native soils and are not associated with environmental degradation under normal soil conditions [22]. Similarly to the elevated Cr, Mo, Ni and Ti concentrations, those elements are originally from a silica sand matrix. The variability of the physical parameters of SFSs can result from differences in mineralogy, particle shape, and fine particle content. [33] It would be logical to assume that tin (Sn) would be also included in the metallic elements typically occurring in foundry sand since it is used in yellow metal / copper based alloys, however, its presence in SFS was not mentioned in the previous research as far as can be ascertained.

3.2.2 Physical properties

Table 3.4 The variability of the physical parameters of SFS

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)[34]	2.53	–	15.5	1.43	16.8	–	$1.2*10^{-8}$	Yes	Yes
Kleven et al. (2000)[35]	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)[36]	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)[37]	2.79	2.36	–	–	–	SP	–	Yes	No
Goodhue et al. (2001)[38]	2.52–2.68	4.75	9.6–15	1.72–1.88	–	SP-SM/ SW-SM/ SC	–	Yes	No
Typical SFS (with clay/silt) (FHWA, 2004)[2]	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 SFS (without clay/silt) (FHWA, 2004)[2]	2.6–2.8	1.18–4.75	8–10	1.60–1.76	11–30	SP	10^{-8}–10^{-4}	Inconclusive	Inconclusive

Note: D_{max}: maximum particle size; G_s: specific gravity; MDD: maximum dry density; OMC: optimum moisture content; CBR: California bearing ratio (a measure of the strength of the subgrade of a road or other paved area, and of the materials used in its construction.); USCS: Unified Soil Classification System.

The morphology of SFS is typically subangular to spherical. According to statistics, the grain-size distribution is uniform: 85%–95% of the material ranges between 0.6 and 0.15 mm; 5%–12% can be smaller than 75 µm. [39] Figure 3.1 shows the particle size analysis for two typical greensand samples. It illustrates that used greensand can provide a range of particle sizes, making it useful for a number of applications. Greensand comprises around 87 - 93% silica sand, 5-8% bentonite clay and 2-8% coal dust or substitute. [9] Its pH ranges from 7 to 9.79. The amount of organic material lost on firing may range from 2-8% [9].

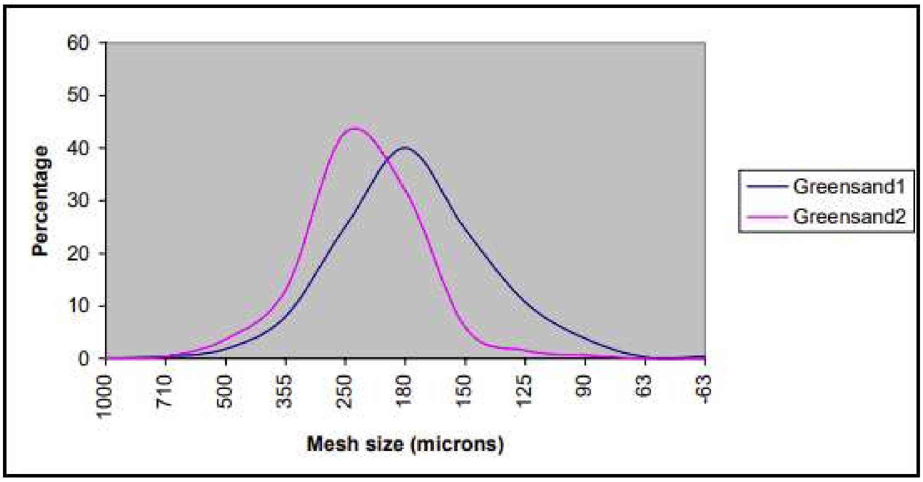

Figure 3.1 Typical particle size distribution for greensand.[40]

Figure 3.2 shows particle size analysis results undertaken for three typical samples of chemically bonded sand: alkaline phenolic, furan, and resin shell (the most popular moulding systems) [9]. Furan sand has a pH of around 2.5 to 4.5, resin shell has a pH of between 4.5 and 7, and alkaline phenolic has a pH of around 10. Due to thermal degradation during metal casting, residual binder in the used sand is usually only a small percentage, less than 1% for furan and alkaline phenolic sands, and between 1% and 4% for resin shell sands. [9]

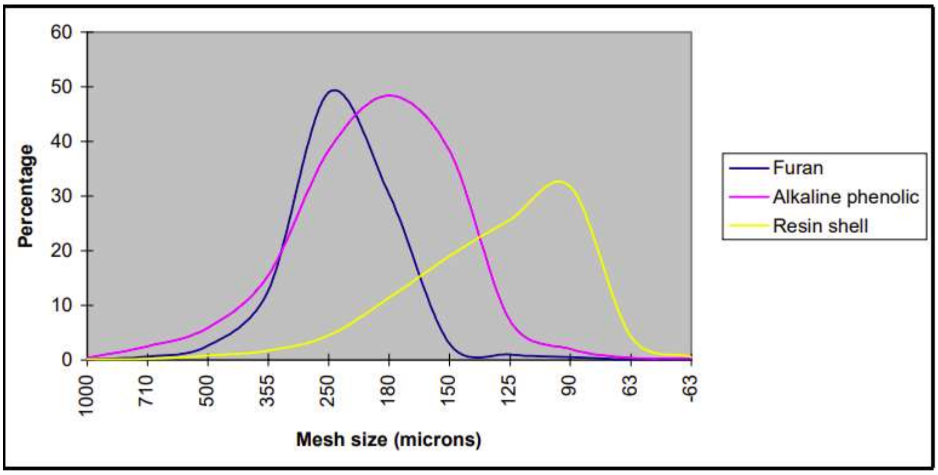

Figure 3.2 Typical particle size distribution for three chemically bonded sands.[40]

4. Use of spent foundry sand in the Foundation Industries

4.1 Current situation

There are many relevant publications and reports on the use of SFS in the FIs. Most recently, in the UK, the Cast Metals Federation (CMF) and University of Birmingham (UoB) reported sustainable management of foundry waste outputs in 2021.[41] That report's literature review indicated that complete replacement of new materials with SFS is not practical. However, it can partially replace raw materials in several applications and FI production, such as concrete, brick, glass and filler applications, and significantly reduce the cost. Most research claimed that SFS is safe for use in the environment, and the standard limits of the chemical and metallic content can be satisfied.

Through communications with foundry industry experts from CMF (Richard Heath and Pam Murrell), Wm Lee Ltd (Adrian Lacey) and John Winter Ltd (Andrew Tagg), the main barrier to large-scale reuse of SFS was also identified in the CMF / University of Birmingham report[41] as inconsistencies in SFS properties and volumes. Meanwhile, the UK's geographically spread foundry industry also increased the recycling cost.

The United States Environmental Protection Agency's (EPA) risk assessment for beneficial uses of spent foundry sands[42] concluded that silica-based spent foundry sands produced by iron, steel, and aluminium foundries can be safely reused to conserve energy, reduce the need for virgin materials mining, and lower costs for producers and end-users alike. The EPA supports the following applications for silica-based spent foundry sands from these foundry types [43]: as an ingredient in manufactured soil, as an ingredient in soil-less media (potting soil); and as a foundation layer of roads (subbase). However, the American Foundry Society estimated that approximately two-thirds of the total US-produced foundry sand waste is disposed of in landfills [32], which implies:

- Shortening the material life cycle resulting in increased consumption of virgin raw materials;
- Saturation of existing landfills and soil pollution in unmanaged landfill cases;
- Release of leachable contaminants absorbed by sand during the moulding process and casting operations;
- Economic impact, referring in particular to logistic costs in SFS transportation (sometimes the landfill is not so close to the foundry); and
- Significant impacts on the environment and climate change (arising) from increased CO_2 emissions owing to aforementioned drawbacks.

According to European Regulations (EC) [44], SFS is classified as non-hazardous waste because even if the total metal concentrations in waste sands are increased with respect to virgin sand, they remain generally low [22]. Two case studies from a report by the Federal Highway Administration in the US are presented here for further reflection:

Case Study 1:

The American Foundry Society (AFS) [2] studied the use of greensand from a grey iron foundry in a Portland cement manufacturer. Chemical analysis was performed to confirm whether the foundry sand met the American Association of State Highway and Transportation Officials (AASHTO) specifications. The chemical analysis revealed that the foundry sand could be an attractive alternative to raw materials for cement kiln feeds. Mixtures were designed using 4.4 wt%, 8.9 wt% and 13.4 wt% of foundry sand. It was found that the chemical characteristics of the clinkers produced with foundry sand differed slightly from those of clinkers produced without foundry sand. The clinkers produced using foundry sand met all the relevant chemical requirements. [2] Setting time and compressive strength of cements were not affected by the presence of foundry sand in the kiln feed. The clinkers produced using foundry sand showed a slight increase in compressive strength. [2]

Case Study 2:

The use of foundry sand in cement production was studied in a commercial report conducted by greensand manufacturer Frazer & Jones in 1994 [2]. 15,000 tonnes of greensand were shipped from New York to a cement manufacturer in Ontario, Canada. It successfully replaced excavated silica materials in manufacturing low-alkali, high-quality Portland cement[2].

4.2 Ceramic applications

Ceramic manufacturing requires mineral sand for various applications. Some studies have investigated the laboratory viability of employing SFS in the ceramics industry [45–47]. As a crucial element of resource efficiency, the circular economy promotes the incorporation of SFS materials into new ceramic production processes [48]. Quaranta *et al.* [46] examined the production of ceramic bricks and tiles with 10–50% foundry sand (applied as aggregates) using the same moulding method and fire curve (maximum temperature of 1000°C) for both product type[46]. According to the findings of that investigation, the optimal proportion of foundry sands in the mixture was 30–40% by weight. This quantity indicated the optimal balance between the maximum possible addition (recovery) of waste and the maintenance of the requisite properties of the ceramic industry's final products, as established for commercial usage. In another report, Alonso-Santurde *et al.*[49] presented their findings, which indicated that the inclusion of these components into the manufacturing of ceramic materials was technically viable and may enhance the properties of the final products [49]. Two types of foundry sand (greensand and core sand) were combined with clay ranging from 0% to 50% and fired at temperatures between 850 °C and 1050 °C to obtain ceramic brick products. They physically and mineralogically evaluated the specimens, analysed the scaling-up, and developed an optimisation study. The physical properties of clay/greensand bricks fired at 1050 °C were considered significantly better than those of their counterparts (clay bricks), although the mineralogy was not appreciably altered. 35% of greensand and 25% of core sand (CS) were determined to be the optimal proportions of sand for bricks of industrial grade, as determined by laboratory tests.

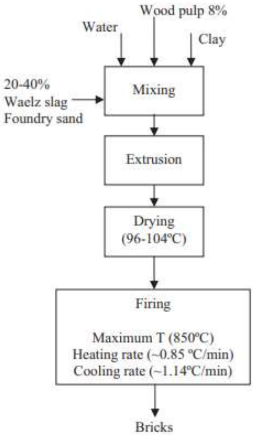

Figure. 4.1 Manufacturing process involved the addition of spent foundry sand to produce red clay bricks. [50]

As shown in Fig. 4.1, some reports have shown the potential of combining several waste materials, including SFS, to produce ceramic products [45, 47, 50]. They have shown that different kinds of waste materials, including spent foundry sand, sediments, stone and granite processing wastes, sewage sludge, fly ash, and steel slag, may be used to manufacture ceramic materials [51–54]. Bragança *et al.*[45] proposed recycling iron foundry sand and glass waste as raw materials for producing whiteware ceramics [45]. They demonstrated that producing triaxial whitewares, using sand from cast iron moulds and cores instead of quartz, white-firing clay and recycled glass waste instead of feldspar, was feasible. Formulations were made containing 50% virgin material (white-firing clay) along with 15–45% moulding sand (cores made with phenolic resin) and glass waste. These parts underwent brief firing cycles at temperatures between 1000°C and 1300°C. Possible environmental impacts of firing this recycled mix containing polluting aromatic compounds (organic binders) were also assessed, through solubility and leaching tests, in accordance with Brazilian standards. The outcomes of that study supported the possibility of producing triaxial ceramics using alternative waste sand materials. For the manufacture of ceramic materials such as refractory bricks, there is a potential use of many forms of industrial waste and by-products based on the ternary system SiO_2–Al_2O_3–CaO. Integration of these wastes with conventional forming processes, such as extrusion, was considered feasible for generating sintered ceramics with potential uses as refractory materials or electrical insulators. Raupp-Pereira *et al.*[47] explored integration of 5–25% foundry sand into a ceramic matrix-like composite made of Al-rich anodising sludge, sludge from the filtration/clarification of potable water, and sludge formed in marble at 1350–1550 °C to produce bricks [47] (shown in figures 4.2 and 4.3).

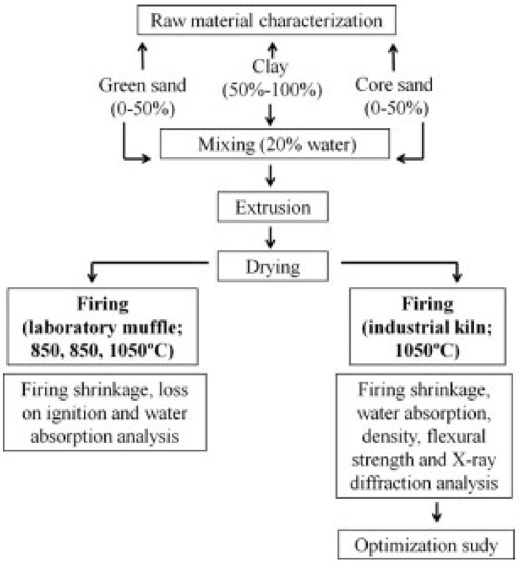

Figure. 4.2 Experimental schematic for recycling of foundry by-products. [49]

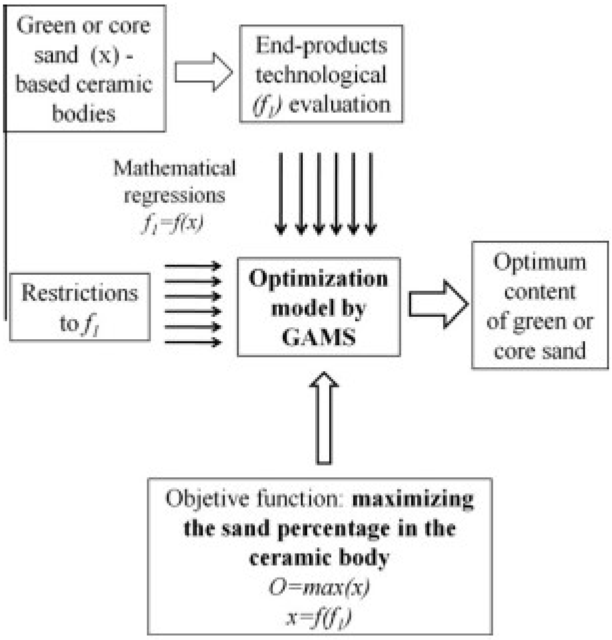

Figure. 4.3. Optimisation flowchart of SFS content in the industrial face-bricks. [49]

In another ceramic application, SFS and Waelz (zinc type waste) slag were substituted for clay to manufacture red clay-based bricks in Spain [48, 50]. These problematic wastes were being disposed of in landfill. A semi-scale industrial trial process with 20–40 weight % additions into raw materials for bricks was completed. Test samples were compared to control bricks produced with no waste additives. Physical-chemical, mechanical, and environmental properties were assessed. Adding Waelz slag and SFS to the mixture permitted the production of more cost-effective and resource-efficient bricks. Compared to samples containing only Waelz slag or SFS, the performance benefits included enhanced extrusion properties during moulding, lower water absorption of the sintered brick due to reduced connected porosity, significant reductions in CO_2 and NO_x emissions during firing, and enhanced potential leachability of some pollutants. However, to fulfil regulatory leaching limitations, it was required to restrict the addition of Waelz slag to less than 30 wt%. Other physicochemical and mechanical properties were unaffected by inclusion of these industrial by-products.

In a recent study, Mymrin *et al.*[55] prepared several sustainable ceramic composites from 0 – 42 wt% of spent foundry sand, 30 – 93 wt% kaolin clay, 0 – 25 wt% of galvanic glass waste, and 3 – 7 wt% of hazardous toner waste [55]. All waste materials were collected from local industries in Curitiba, Brazil. Ceramic composites were sintered at 1100, 1150, 1200, 1250, and 1275 °C. The flexural resistance of the ceramics reached a maximum of 12.29 MPa, the linear shrinkage ranged from 2.99% to 11.20%, and the water absorption ranged from 19.90% to 10.85%. These properties meet Brazilian Technical Norm NBR 7170. [55] Different analysis techniques showed the production of glassy structures, including mullite and cristobalite crystalline structures. The analysis of the chemical composition of the gases emitted during ceramic firing at 1275°C using atomic absorption spectroscopy, as well as the analyses of solubility and leaching of metals from ceramics, revealed that the developed composites and technology were fully compliant with Brazilian sanitary standards. It was concluded that utilising spent foundry sand and other waste materials as useful raw materials for the production of sustainable ceramics with high chemical, mechanical, and physical properties could reduce environmental pollution.

New composites of environmentally clean glass-ceramics and construction materials can be readily produced by incorporating spent foundry sand and hazardous materials [56–58]. Mymrin *et al.* [58] developed new composites of glass-ceramics from hazardous Cr-Zn galvanic sludge (up to 30 wt%), spent foundry sand (25 wt%), glass rejects from metal surface cleaning (20 wt%), and natural red clay (25 wt%). After sintering at temperatures between 950 °C and 1200 °C for 1 hour, the ceramic product exhibited exceptionally high flexural resistance (up to 22.84 MPa) and low values of linear shrinkage (5.02%), water absorption (3.20%), and bulk density (2.00 g/cm^3), which is better than Mymrin *et al.'s* [59] new ceramic composites from sewage sludge, foundry sand, glass waste, and acid neutralization salts, for which flexural resistance was up to 12.52 MPa, density varied was between 1.73 and 1.81 g/cm^3, water absorption was between 13.4 and 20.3%. The solubility and leaching of heavy metals from composites manufactured from 75% industrial wastes were far below Brazilian regulatory limits; hence they were considered environmentally benign based on those regulations. The manufacture of facing tiles, roof tiles, blocks, and bricks could be economically effective based on the aforementioned outcomes. Silva *et al.*[57] utilised discarded SFS and inorganic waste from the cellulose and paper industries to manufacture glass-ceramic materials. The glass-ceramics were formed at various temperatures (885, 961, and 1090 °C). The main developed phases were cristobalite, α-wollastonite (parawollastonite), and β-wollastonite (pseudowollastonite). The glass-ceramics demonstrated significantly improved properties, such as low water absorption and apparent porosity (0.26 to 0.88 wt% and 0.66 to 1.77 vol%, respectively). Regarding construction ceramics materials, Alekseev *et al.* [56] showed the potential for manufacturing new red ceramic composites from red mud of hazardous bauxite waste (50–100 wt%) and SFS (10–50 wt%) [56]. After sintering at 1150 °C, linear shrinkage ranged between 6.62 and 7.92 %, water absorption varied between 2.77 and 14.41 %, and bulk density was determined between 1.65 and 2.07 g/cm^3, which is reasonable compared to Mynrin *et al.*'s research. [59] Due to the total neutralisation of heavy metals from both industrial wastes, the most important attribute of the developed ceramic composite was its environmental stability.

SFS could replace natural quartz sand, which is commonly utilised as additives in ceramic plastic bodies that are shaped into ceramic-based building components [60]. The main concern is that the technique of processing sand mix does not remove binder agent residues from the surface of the quartz matrix grains used to produce a green mix. Consequently, the binder agent's thin, adhesive, and water-insoluble coating remains on the sand grain surface. The oxidation of organic-based binder agents during heat treatment / firing of ceramic materials can lead to the emission of hazardous substances (e.g., dioxins and furans). Therefore, for application, these emissions should not exceed the admissible values. Pytel [60] evaluated the potential application of recycled core and moulding sands to production of ceramic building materials, which were manufactured from plastic bodies (silty mineral in the form of tertiary Krakowiec clay (IKK)) containing various amounts of spent sands, applied as leaning additives [60]. The study addressed the possible dangers involved with the production and disposal of these substances. Atmospheric emissions of dangerous gaseous chemicals in the form of polycyclic aromatic hydrocarbons (PAHs) as derivatives of organic binders used in moulding and core sand mixtures are a potential threat. These compounds are generated during the firing process of ceramic materials or with the release of heavy metals from the ceramic matrix. Under the specified circumstances, this procedure may occur over the full-service life of ceramic items. Characteristics of the resulting ceramic materials and positive test results indicated low-level heavy metal leaching and the absence of hazardous atmospheric emissions. These findings demonstrated the possible use of reclaimed sand as a leaning admixture and a useful component in ceramic plastic bodies for manufacturing construction materials.

More recent investigations have further demonstrated the main options for spent foundry sand reuse in replacement of fine aggregate in brick furnaces [61–63]. Hossiney *et al.*[63] utilised spent foundry sand from a reclamation plant in Belgaum, Karnataka, India, to produce bricks at a brick manufacturing facility with a monthly output capacity of roughly 50,000 bricks [63]. As shown in Figure 4.4, up to 50 wt% of spent foundry sand was introduced to manufacture bricks with the required properties. Bricks containing 50 wt% spent foundry sand and fired at 900 °C had the lowest average wet compression resistance of 3.31 MPa and the highest average water absorption of 21.6%, which could be categorised as Class III bricks according to the IS 1077 standard specification[63]. The apparent porosity, water absorption, and specific gravity of bricks containing spent foundry sand were not significantly different from those of commercial bricks. The inclusion of spent foundry sand decreased the bricks' bulk density, resulting in a decrease in compressive strength. In accordance with the IS 1077 standard specification [63], spent foundry sand bricks could be categorised as Class III bricks. These bricks could be utilised in single-story load-bearing constructions and multi-story framed structures to construct infill walls. For geopolymer brick production, Apithanyasai *et al.*[62] used foundry sand with fly ash and electric arc furnace slag (collected from some companies in Thailand) and investigated their best ratio [62]. Their findings indicated that the geopolymer bricks with the maximum compressive strength were those blended at a ratio of 40:30:30, with a strength of 25.76 MPa. Moreover, a life cycle assessment from cradle to grave was conducted that proved the lower environmental impact of geopolymer brick production in every aspect (climate change, human toxicity, fossil fuel depletion, ozone depletion, terrestrial acidification, and terrestrial ecotoxicity) compared to that of concrete production. Recently, Aneke [61] prepared PET (polyethylene terephthalate) plastic waste bricks through different proportioning (PET waste: spent foundry sand) of 20%, 30%, and 40% of the foundry sand dry mass. The produced bricks were compared to fired clay bricks to assess their load-bearing capacity under compression and tension. An appreciable strength was achieved by the waste-made bricks, which was about 1.5–2 times higher than that of fired clay bricks. They concluded that the production of masonry bricks using a mixture of PET waste and spent foundry sands proved to be a promising approach.

Most studies focused on incorporating spent foundry sand into clay-based bricks and gave less attention to its analysis and characterisation. Although this provides fundamental data for assessing the suitability of spent foundry sand for refractory application, a detailed examination of spent foundry sand, such as microstructural evolution during heat treatment, has not received adequate attention. For this purpose, Xiang *et al.* [64] systematically analysed spent foundry sand supplied by a plant engaged in zircon extraction from used foundry sand rejected during investment casting in Guangdong province, China. The microstructural evolution of spent foundry sand specimens subjected to heat treatment between 1300 and 1550 °C was examined. The quantitative study of the crystal phases revealed that the spent foundry sand comprised 46.2% mullite, 28.1% cristobalite, and 10.9% zircon; the predominant oxidation states of Fe and Ti in SFS were Fe_3O_4 and TiO_2. Leaching of spent foundry sand was the main concern because it can contain potentially toxic elements [65] as stated above in Section 3.2.2; nevertheless, thermal treatment below 1500 °C was safe according to the research of Xiang *et al.* [65]. For specimens sintered at 1500 °C, the change from tetragonal ZrO_2 to monoclinic ZrO_2 reduced the cold modulus of rupture, whereas Fe_2O_3 decomposition at 1550 °C reduced the bulk density and modulus of elasticity. Changes in phases had a substantial effect on the true density, and the melting of cristobalite at 1550 °C caused a considerable decrease in density.

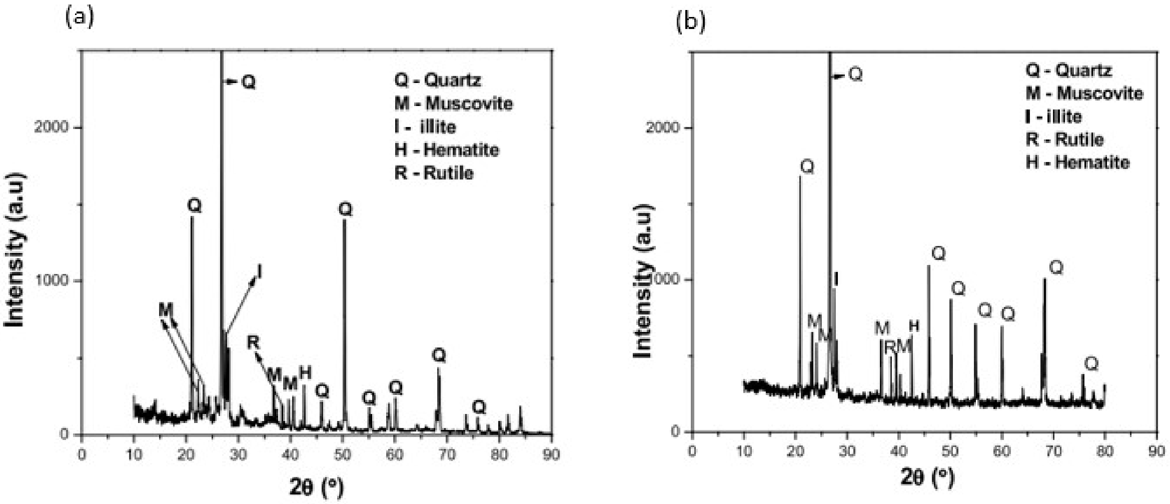

Figure. 4.4 XRD patterns for ceramic bricks produced using (a) 0% SFS and (b) 50% SFS. [63]

Producing ceramic coatings using spent foundry sand is another potentially promising application. A recent study by Souza *et al.* [66] made good use of spent foundry sand. This study utilised spent foundry sand acquired from the sand exhaust system of a foundry plant in Joinville, Santa Catarina State, Brazil. Without any prior treatment, this powder was utilised to prepare the electrolytic solution required for coating. Coatings were applied to 5052 aluminium alloys using the electrolytic plasma process by applying a potential difference of 650 V and a frequency of 300 Hz, with deposition durations of 300 and 600 s. Regardless of the deposition duration, the coatings obtained from this residue consisted primarily of Al, Mg, Si, P, Ca, Fe, K, Ti, and Na, producing a ceramic material whose crystalline structure was dominated by alumina and quartz. The crystalline silicon was in the form of moissanite (SiC), which led to improved mechanical properties of the coating. Increasing deposition time and electrolytic solution concentration led to a rise in the coating's contact angle, roughness, thickness, and resistance to wear.

In terms of energy saving and fuel reduction, spent foundry sand could help reduce the kiln firing temperature for the production of clay-based ceramic tiles. Lin *et al.* [17] studied the effect of firing temperature on sintered ceramics fabricated from clay and spent foundry sand. In this investigation, clay was substituted with 0 or 15 wt% spent foundry sand in the production of tile samples. They fired samples at four different kiln temperatures (1000, 1050, 1100, and 1150 °C). The test findings revealed that employing 15% spent foundry sand in the tile specimens allowed for a 50 °C reduction in kiln temperature. This drop in temperature could be beneficial for reducing fuel costs, energy usage and carbon emissions. Additionally, the acid-alkali resistance of the tile samples produced using 15 wt% spent foundry sand was enhanced because the weight loss of the reclaimed tile specimens (~1 wt% after 14 days) was half that of the regular specimens (~2 wt% after 14 days) after immersion in acidic and alkaline solutions. The effects of temperature on the physical and mechanical characteristics of ceramic composites produced using spent foundry sand waste was further investigated by Roa *et al.*[67]. They studied and modelled the influence of temperature on the water absorption, linear shrinkage, density, and compressive strength of ceramic composites generated by mixing clay with 20 to 40 wt% foundry sand waste. Prototypes were formed by uniaxial pressing and burned at three different temperatures (850 °C, 950 °C, and 1100 °C). At 1050 °C, properties including mechanical strength and density achieved their maximum levels, which may be attributed to the decrease in pore size inside the composites' microstructure during calcination.

4.3 Glass applications

Much research has been published on the use of SFS in cements and ceramics. By comparison, few studies have focused on the use of SFS in the production of glass materials.

4.3.1 Sand for glass manufacture and foundries in the UK

This option for a potential use for spent foundry sand is considered here due to the original sources of sand for glass manufacture and foundry sand being quite similar but arising in different grades/qualities/sizes etc. In Britain, only the Cretaceous Loch Aline sands are suitable for high-grade glass tableware and laboratory ware, achieving purities of 99.8 wt% SiO_2. The purity of these sands justifies the underground mining of a bed 10 m thick, which contains pure, white, poorly cemented sand. Quaternary sands, especially those of

Cheshire and Lancashire, are an important source for other grades of sand, supplying the float and container glass industries [68]. The essential requirements for silica sand for glass manufacture are: (i) it must have an even grain size: more than 90% of the grains must lie in the range 125-500 µm; and (ii) the maximum Fe_2O_3 content for coloured container glass is less than 0.25wt % [68]. Sands that fail to meet the requirements of the glass industry may be sold for other applications, such as foundry sands used for preparing moulds for metal casting: the focus of this study. The British Standard requirements for particle size, and chemical and water contents for colourless glass production are presented in Table 4.2.2.[41]

Table 4.3.1 Chemical composition of silica sand for glass manufacture and foundry sand.[69]

Component (wt %)	From Cheshire	From Lancashire	From Cheshire
	For float glass	For coloured glass	For foundry sand
SiO_2	97.5	95.1	97.0
Al_2O_3	1.3	2.25	1.63
Fe_2O_3	0.105	0.35	0.15
Cr_2O_3	0.001	-	-
TiO_2	-	0.11	0.06
CaO	0.1	0.18	0.11
MgO	-	0.13	-
Na_2O	0.1	0.28	0.14
K_2O	0.6	1.1	0.74

Table 4.3.2 Sand requirements for soda-lime colourless glass based on BS 2975 [41].

Parameter	**% by weight**
d>1mm	0
d>0.75mm	<0.25
d>0.5mm	<0.5
D<0.12mm	<5
D<0.09mm	0
SiO_2	98.8±0.2
Al_2O_3	0.2-1.2
Fe_2O_3	0.03-0.003
Cr_2O_3	0.0005
C	0.1
Water content	4.5±0.5

In processing silica sand for glass and foundry applications, it is important that the parent material is reduced to its natural grain size intact and that impurities are liberated for subsequent removal [70]. In previous studies [70, 71], a beneficiation procedure involving comminution, wet milling, scrubbing, washing, flotation, and magnetic separation was satisfactory. A flowsheet outlining each beneficiation phase is presented in Figure 4.5. In general, scrubbing successfully reduced the alumina and iron oxide content of most sand samples, and iron oxide and alumino-silicate minerals responded well to flotation.

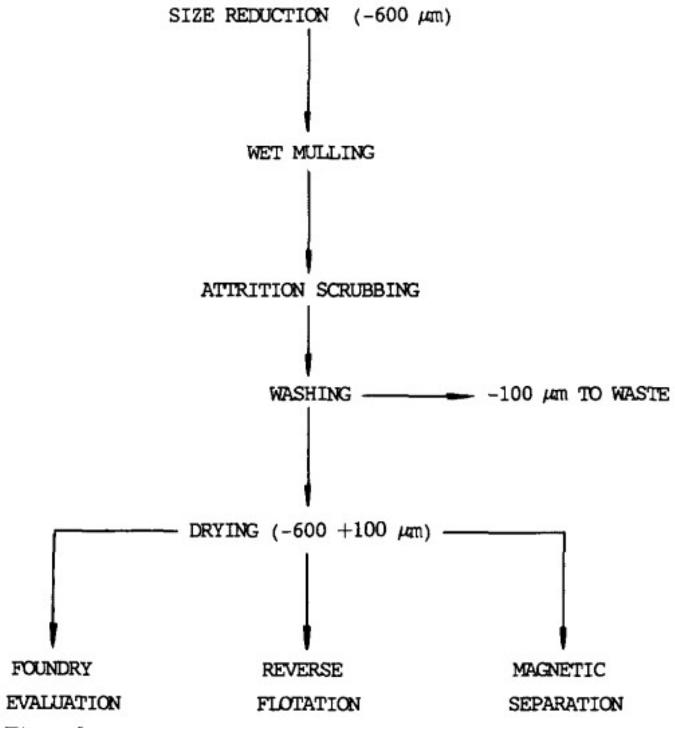

Figure. 4.5 Generic silica sand process flowsheet. [70]

4.3.2. Mineral wool

Mineral wool (also known as stonewool or rockwool) is a glassy material generated by melting raw materials at high temperatures. Thus, it has many of the same issues regarding CO_2 release as traditional commercial glass products such as soda-lime-silica containers and flat or fibre glasses. [72] Mineral wool production has been estimated to be approximately 2.0 to 2.5 MT per year in the EU. [73, 74] Minerals, primarily basalt, and other raw materials are typically mixed and then melted inside a modified blast furnace to produce a molten oxide slag. The (glass-forming) molten oxide slag is then poured onto rapidly rotating wheels (at many thousands of rpm), which causes the formation of long filaments or fibres as the melt is spun from the surface of the wheels and rapidly cooled to form the glass filaments. These filaments or fibres are collected into mats and coated with an organic binder, forming the mineral wool insulation material. [75]

Mineral wool presents a potentially valuable route for spent foundry sand to be used in glass production for two primary reasons: firstly, mineral wool has less stringent requirements on colour (which is primarily dictated by the transition metal content of the raw materials, e.g., Fe) compared to float, fibre and container glasses; and, secondly, industrial waste materials are already used in the manufacture of mineral wool, e.g., slag material from steelmaking, concrete, brick chips, waste glass, and similar materials, to replace virgin minerals such as quartzite, granite, and coal fly ash. [76–78]

Mineral wool fibres are commonly used to reinforce other materials, such as building material insulation, and are similar in this regard to fibreglass.[76–78] SFS could conceivably serve as a source of silica in the mineral wool production process.[79] They are produced by combining blast furnace slag with silica or alumina in a cupola furnace and then fiberizing the molten material.[80] To be used in production, the SFS may need to be pre-treated and / or consolidated into pellets or briquettes to meet size requirements for the raw materials used in mineral wool manufacture. SFS could also potentially be used to manufacture non-optical structural fibreglass. Fibreglass is produced by melting silica sand and other raw materials, or re-melting culet, and drawing the molten material through a platinum bushing with small apertures, thereby forming the desired glass fibres.[79]

Patent US8697588B2 “Mineral wool from recyclable materials” [80] disclosed an invention for forming mineral wool using 5-22% foundry sand by dry weight. In Turkey, spent foundry sand was used to produce mineral wool and fibreglass [79]. In 2014, Martin provided a method to manufacture mineral wool from recyclable materials [80].

4.3.3 Container glass

Since greensand is a mixture of silica sand, clay, powdered coal, and water, it has rarely been used as a raw material for container glass production, even for amber or green glass. In 1993, Skrynnik *et al.* [81] researched and reported the possibility of using used SFS in glass production. The investigations indicated that the spent foundry sand could be used as raw materials for commercial glass. The particle size, chemical composition, and stability of SFS samples in their research were investigated and found suitable for glass production. They noted that, from the point of view of any waste being suitable for use in the glass industry, it should satisfy the following primary requirements:

- The volume of waste should be larger than or equal to the minimum annual requirement of this feed material for one glass plant or one unit in a glass plant;
- There must be guaranteed stability of the supply of waste to ensure continuous operation of the glass plant;

- The presence of refractory materials (chromite, magnetite, lanthanum, zirconia, etc.) and toxic impurities cannot be tolerated in the waste;
- The concentrations of pigment impurities must not exceed the permissible limits;
- Variations in the concentrations of the primary materials in alkali-containing wastes should not exceed +/- 0.5% for soda wastes, +/- 6% for sulphate wastes, and +/- 2% for soda-sulphate and complex wastes;
- The use of the waste should not require the installation of expensive additional equipment;
- The price of the waste should not exceed the current price for the usual forms of mineral raw materials.

They noted that spent foundry sands satisfy practically all of the requirements listed above. Visual analysis of the lab-produced container-type glass samples showed that it was possible to obtain homogeneous, transparent glass without visible bubbles or cord. No increased foaming or disturbance of the fining process was observed. The glass obtained had a light green colour due to the presence of iron oxide. They concluded that SFS could be used as a complex raw material for producing silicate glasses.

In 2004, Zanetti *et al.* [82] reported a reclamation process applied to the green moulding sands from the Teksid S.p.A. cast iron foundry in Crescentino (Vercelli, Northern Italy). A wet-mechanical treatment of 500 tonnes of SFS was performed in the Sasil plant in Brusnengo (Biella, Northern Italy), which belongs to the Gruppo Minerali S.p.A. (Novara, Northern Italy). The industrial recycling of the reclaimed foundry sand was proposed both for core making through the cold-box process and for producing colourless glass.

In 2016, Martin *et al.* [83] researched the possibility of partially replacing soda-lime-silica glass silica raw material by SFS. After treatment, a 25% replacement of silica by a particular SFS was shown to be possible and resulted in a green glass due to the presence of iron (Figure 4.6). However, there was some difficulty in colour control, suggesting that, as would reasonably be expected, further research and some degree of optimisation at multiple stages would be required to realise this new waste-derived raw material for use in industrial-scale glass manufacture.

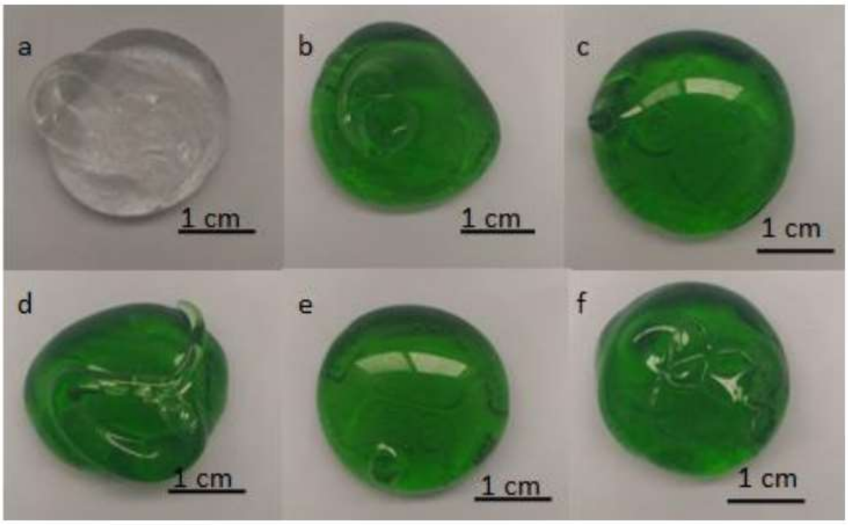

Figure. 4.6 Glass made in lab conditions with SFS; a) Benchmark 0% SFS; b) 25% ADF1; c) 25% ADF2; d) 25% ADF3; e) 25% ADF4; f) 25% ADF5. [83] Note: ADF1 to 5 are the names of different kinds of foundry sand in Martin's research. [83]

4.3.4 Glass-ceramics

Glass-ceramics contain one or more crystalline phases dispersed in a glassy phase. They are produced by controlling the crystallisation using isothermal and non-isothermal methods.[84] A comprehensive review of ceramics was covered in Section 4.2. Further discussion here focuses on the SFS impact on the glass-ceramics/frits forming properties.

In 2020, Silva *et al.* [57] reported their research on utilising SFS and inorganic waste from the cellulose and paper industries to manufacture glass-ceramic materials. The precursor glasses were obtained by the melting/cooling method for further crystallisation. 70 wt% of SFS was introduced to prepare two different kinds of frit, as shown in Fig. 4.7, which had a dark green colour. This fact can be associated with the presence of iron oxide in the chemical composition of the precursors. Unfortunately, the melting temperature of the frits was not given in the publication. The glass-ceramics were formed at various temperatures (885, 961, and 1090 °C). The main developed phases were cristobalite, α-wollastonite (parawollastonite), and β-wollastonite (pseudowollastonite). The glass-ceramics demonstrated significantly improved properties, such as low water absorption and apparent porosity (0.26 to 0.88 wt% and 0.66 to 1.77 vol%, respectively). Water absorption of ≤0.5% classifies this glass-ceramic material in group BIa of the Brazilian standard for porcelain tiles.[85]

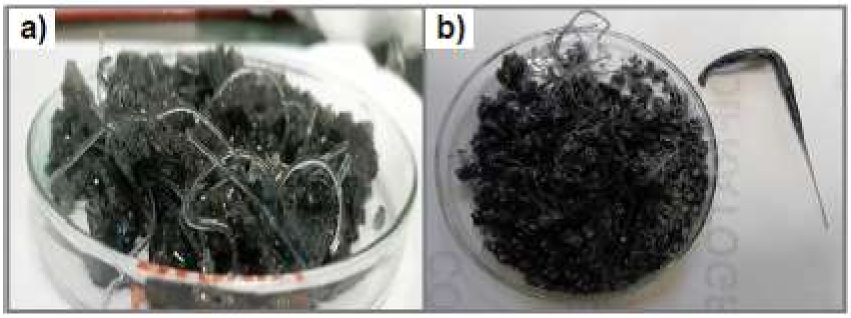

Fig. 4.7. Images of frits (glasses) produced by mixing SFS and inorganic cellulose wastes: a) glass A (with grits); and b) glass B (with lime mud). [57]

4.4 Cement and building / construction materials

4.4.1 Portland cement

Global cement production totals 4.3Gt and is set to grow by 12-23% by 2050 from current levels. [86] The Global Cement and Concrete Association predicts that cement consumption may increase by even 40% compared to 2020 to reach 5.9 Gt [87]. Cement production in the UK accounted for between 8-9 Mt on average from 2001 to 2021 [88] and was responsible for 1.5% of territorial greenhouse gas (GHG) emissions on average from 1990 to 2018 (or 1.86% if in 2018) [89]. Approximately 85-90% of cement production in the UK is Portland cement with 95% Portland clinker content.[88] When hydrated, Portland cement reacts chemically with water, causing it to set and harden. When mixed with fine and coarse aggregate, concrete is formed. There are several specifications for Portland cement, as designated by ASTM C150 [90] and ASTM C1157 [91] or EN 197-1 [92] and EN 197-5 [93].

Portland cement is manufactured using materials with the appropriate proportions of calcium oxide, silica, alumina, and iron oxide. Ranges of principal minerals in European Portland clinkers (a solid material produced in the manufacture of Portland cement as an intermediary product), 95% of Portland cement, are shown in Table 4.4.1. These ingredients are found in natural rocks such as shale, dolomite and limestone.

Table 4.4.1 Ranges of principal minerals in European clinkers [94]

Shorthand nomenclature	Chemical formula	Mineral name	Typical level (mass %)	Typical range (mass %)
C_3S	$3CaO·SiO_2$ or Ca_3SiO_5	Alite	57	45–65
C_2S	$2CaO·SiO_2$ or Ca_2SiO_4	Belite	16	10–30
C_3A	$3CaO·Al_2O_3$ or $Ca_3Al_2O_6$	Aluminate	9	5–12
C_4AF	$4CaO·Al_2O_3·Fe_2O_3$ or $Ca_4Al_2Fe_2O_{10}$	Ferrite	10	6–12

Environmental Protection Agency [2] guidance suggests that SFS can be used for Portland cement production as the silica content equals or exceeds 80 wt% and includes aluminium and iron oxides – the main Portland cement constituents.[2] Also, it is a low-alkali material, which is beneficial for Portland cement production. [2] Some limitations and barriers identified during the TransFIRe project that may limit the use of SFS in the production of Portland cement (clinker) are:

- Raw materials with consistent chemical compositions are easily accessible (also pointed out in a previous report [2]);
- Consistency in high volume deliveries of foundry sand can be an issue (as mentioned in a previous report [2], approximately 10,000–40,000 tonnes annually for a plant);
- The presence of toxic (Cr) and heavy metals (Hg, Cd, Tl) can be of concern environmentally;
- Possible high levels of volatile organic compound (VOC) and total organic carbon (TOC) can cause SFS to fall into the “gap” between being a fuel and a raw material;
- VOC/ TOC can bring the environmental risk of high TOC readings at the stack as these compounds will volatilise at the top of the preheater system and dissipate up the stack, rather than provide any useful energy to the process;
- The grinding issue - depends on the VOC/TOC, the siliceous properties of the other raw materials, and the grinding technology employed at the cement plant; and
- Cost issues (also noted in [2])

SFS could potentially be considered a silica source and might be accepted by cement manufacturers if high volumes are assured, and the price is competitive. Before use, compatibility with other raw materials should be assessed. In addition, chemical oxide and Toxicity Characteristic Leaching Procedure (TCLP) analyses must be undertaken[65]. Limestone, silica, and clay are common materials used to produce clinker and cement[95]; therefore, SFS could potentially be a silica, alumina and iron source. It could partially offset the need for virgin silica as well as iron and alumina sources. However, particle size may be an issue and requires further consideration. To use SFS in cement manufacture, it has to be separated from other foundry by-products. The oversized material that does not pass the screens, "core butt," consists of chunks and grains of coarse sand and scrap metal. Most cement plants require the “core butts” to have uniform grain size by grinding. Metal in the stream is removed using a magnetic separator. To meet the demand of a single cement plant, SFS with similar properties from several foundries should be stored at one storage site.

The specific lifecycle impacts of spent foundry sand used as a raw material in clinker production should be determined at the preparation stage and then confirmed during the operation stage.[96] In addition, spent foundry sand may substitute for the other secondary materials (e.g., blast furnace slag, CCPs, cement kiln dust, etc.).[96]

4.4.2 Blended cement

Current European cement standards BS EN 197-1 [92] and BS EN 197-5 [93] include six main types of cement and 32 types of common cement containing clinker (K), blast furnace slag (S), silica fume (D), natural and natural calcinated pozzolana (P and Q, respectively), siliceous and calcareous fly ash (V and W, respectively), burnt shale (T) and limestone (L, LL). Current U.S. standard ASTM C595/C595M - Standard Specification for Blended Hydraulic Cements [97] allows using blast-furnace slag, natural pozzolan and limestone. Both European and US standards do not list sand or SFS as a main (more than 5%) or minor additional constituent (less than 5%); therefore, nowadays, it cannot be used in blended types of cement based on the definitions given in these standards.

4.4.3 Concrete

Concrete, the world's most extensively used construction material, is the backbone of all construction and development activities worldwide. Each of the primary constituents of concrete has an environmental impact to a different extent. Overall, concrete accounts for approximately 7% of global carbon dioxide (CO_2) emissions and 4% of greenhouse gas (GHG) emissions. Since concrete is widely used worldwide, its use has led to different sustainability issues [15]. Sand accounts for approximately 25 volume% and 30 wt% of concrete[98]. Global use of concrete is estimated to be as 35 billion tonnes. Hence, the sand used for concrete alone weighs 10.5 billion tonnes. Annual concrete consumption in the UK is estimated at 80 Mt [99] with approximately 24 Mt of sand.

The concrete standard BS EN 206 “Concrete specification, performance, production, and conformity” [100] allows using aggregates and additions (incl. mineral fillers and pigments) conforming to BS EN 12620 “Aggregates for concrete” Table A.1 in this standard lists foundry sand (F) as a material with a positive history of use, with no special requirements in a standard but with additional requirements identified for inclusion. Therefore, SFS is provisionally within scope, pending the inclusion of suitable test methods and requirements. Nevertheless, the current study shows that foundry sand can be used in concrete to improve its strength and other durability factors as well as in cement mortar [101, 102 98]. ASTM C 33-03 "Standard Specification for Concrete Aggregates" [103] gives limits for deleterious substances in sand aggregate for concrete: clay lumps and friable particles 3% by mass, coal and lignite 1% and material finer than 75-µm: 3% and 5% for the concrete subject to abrasion and all other concrete, respectively.

Foundry sand, blended with natural or other suitable fine aggregates to meet grading requirements, has been reported to be used in cement-based flowable fill applications in the Buffalo, New York area, Pennsylvania, USA. Foundry sand was free from debris materials such as wood, garbage, and metal. It satisfied the specified limited strength criteria [104].

Over recent decades, much research has been conducted on the mechanical, chemical and durability aspects of foundry sand. Ahmad *et al.* [15] conducted a comprehensive review of studies on using spent foundry sand (SFS), both green and chemically bonded, for concrete applications. They conducted 19 studies on the fresh and mechanical performance of concrete with SFS, one on acid resistance, one on density, and one on carbonation depth. They found that adding SFS at up to 30% enhanced the durability and mechanical strength of concrete to some extent but at the same time reduced the workability of fresh concrete as the replacement level of SFS increased. They concluded that:

- There was almost no difference in bulk density, specific gravity, or grain size distribution between SFS and natural sand.
- The flowability of concrete is reduced with the substitution of SFS. Due to the porous nature and larger surface area of SFS, water demand increased during concrete mixing. Workability was acceptable with up to 30% substitution of SFS. Beyond 50% SFS substitution, the concrete mix required higher doses of chemical admixture (plasticizer). It was possible to produce self-compacting concrete (SCC) with fly ash and SFS by replacing Portland cement up to 100% by volume, with a significant increase in the amount of superplasticizer [13, 105].
- SFS can be used up to 30% instead of natural river sand with no harmful influence on concrete strength. The micro filling provides more dense concrete, leading to more resistance to load. The early strength (up to 28 days) and long-term strength (90-365 days) were usually higher than the reference sample. A decrease in strength at a

higher dose of SFS (beyond 50%) was due to difficulties in compaction (low workability, more pores after compaction).

- Due to the dense matrix, improvement in the durability (water absorption, acid resistance, density, and carbonation depth) of concrete with SFS was observed.

Additionally, other studies showed that:

- The shrinkage of concretes with SFS mixes is higher than conventional concrete, and the modulus of elasticity is similar to the strength results [106] [107].
- With different SFS replacements, a variation of split tensile strength is similar to compressive strength. [108] [109] [29] [110] [111] [112] [113] [25]
- Flexural strength for different SFS replacements correlates well with compressive strength results [114].
- An increase in permeability with an increase in the percentage level of SFS is observed with a significant increase beyond the 30% replacement level with SFS [114].
- An increase in carbonation depth is found significant as the introduction of SFS beyond 30% [27] [111], mainly due to the poor workability and as a result, poor compaction (a continuous porous system).
- As SFS replacement increases, so does chloride ingress.
- The salt-scaling resistance of concrete mixes with up to 20% SFS is comparable to the reference mix. For SFS levels of 43% and above, salt-scaling resistance decrease significantly [115].
- Paving stones with 35% SFS passed the ASTM abrasion requirements [116]. Abrasion resistance improves in concrete mixes containing fly ash, with SFS up to 47% by weight [115].
- A decrease in wear depth with an increase in SFS content which further decreased with an increase in curing time [29]

Greensand SFS is typically black. The introduction of greensand may cause the finished concrete to have a greyish / black tint, which may not be appropriate if a specific consistency of colour, or a specific colour, is required. A 15% fine aggregate replacement with foundry sand produces a minimal colour change. Also, the foundry must be able to consistently and confidently meet the quantity requirements of the concrete manufacturer.

4.4.4 Asphalt

Over 25 million tonnes of asphalt (asphalt concrete) are produced annually in the UK. Typically, the aggregate constitutes 90–95% of the total mixture, and the asphalt cement (asphalt binder) constitutes 5–10% of the total mixture to form the asphalt concrete [117].

Specifications for aggregates for bituminous mixtures are included in BS EN 13043:2002 [118]. Bridgewood and McKie [119] showed that SFS was very close to the limit values of the standard and to being classed as inert for BS EN 13043. The limiting factor was the sand's grain size distribution, which led to the finer fraction being used in asphalt production. Based on the literature for other foundry sands, only a very few would meet BS EN 13043 requirements. They concluded that a re-use application could be identified. Foundry sand can also be used as fine aggregate in hot mix asphalt pavements. Satisfactory performance has been obtained from hot mix pavements, asphalt concrete, incorporating up to 15 % clean, spent foundry sand [104, 120]. Dyer *et al.* [121] analysed 26 studies on the use of SFS and presented the technical, environmental, economic, and management characteristics of using SFS as fine aggregate in hot mix asphalt (HMA). They found that:

- The physical characteristics of SFS are similar to the fine aggregate used in HMA, according to research and technical criteria;
- The SFS microstructural properties of uniformity, particle size, and shape distribution benefit the HMA mechanical properties;
- SFS consists of silica with low concentrations of metals and phenolic resins from the foundry process (for chemically bonded sands), without another toxic substance;
- The mechanical properties of HMA containing SFS as fine aggregate met the main technical criteria in most studies;
- The asphalt binder isolates the SFS particles, eliminating the environmental risk of contamination by leached wastewater from HMA and producing a road that is environmentally safe;
- The mechanistic empirical properties of HMA containing SFS as fine aggregate met the technical criteria for heavy traffic of vehicles, resistance to repeated loads, and weather variations conditions;
- SFS reuse produces direct economical benefits in the waste discard chain and road construction;
- In the same way, SFS reuse produces environmental benefits, with a considerable reduction of the global environmental footprint;
- The management system to coordinate SFS reuse requires simple technology and low budget to comply with the main environmental legislation

ASTM developed a standard that helps the road and paving industries make better use of foundry sand in asphalt mixtures [122]. The guide covers the physical and chemical requirements (e.g., grading, shape, density, toxicity) of virgin or recovered foundry sand used in asphalt mixtures.

4.4.5 Geopolymers

Doğan-Sağlamtimur [79] found that the physical and mechanical properties of the geopolymer building materials produced by using Na_2SiO_3 or NaOH binder and SFS were similar. They concluded that SFS-based geopolymer materials are suitable for building wall materials.

4.4.6 Road construction

Yazoghli-Marzouk *et al.* [123] showed that that foundry sand treated with 5.5% hydraulic binder (cement) provided acceptable mechanical properties while having no environmental impact. Their investigation demonstrated that this foundry sand could be used in sub-base layers as road materials.

4.4.7 Soils

Specification for topsoil is included in the BS standard BS 3882:2015 [124] Bridgewood and McKie [119] showed that the total analysis of the SFS alone demonstrated very low levels of heavy metals, which were within the Soil Guideline Values and within BS3882. They concluded that a re-use application in topsoil could be identified. The reuse options would depend on the threshold concentrations and the risk involved in the particular reuse.

4.4.8 Structural fill and subbase layer of pavements

Vinoth *et al.* [125] found that SFS stabilised with 6% cement can be used to construct a subbase. They also found that SFS stabilised with 1.2% cement could be used as structural fill. However, cement content could vary depending on the nature of the foundry sand.

4.5 Foundry / metals sector

4.5.1 Reclamation of SFS

A recent report addresses the challenges that U.K. foundries face in sustainably managing waste products such as SFS and dust [41]. According to the results, all foundries across the U.K. carry out some form of reclamation to process their waste. Regardless of the method, some new sands are continually required for the casting process. Therefore, some SFS will always be taken out of the system, usually sent to landfill. Reclamation efficiency depends on a wide range of factors, including the type of reclamation, sand, and binder. The most common binder systems in UK foundries are alkaline phenolic, followed by furan (see **Section 3.1**). In using the alkaline phenolic binder system, achieving a recovery rate higher than 70-80% with simple dry attrition is challenging. However, thermal recovery could lead to a recovery rate of around 96% in modern plants. [41] These plants are expensive, and the running cost is relatively high. Depending on its size, standard thermal reclamation plant would cost between £150k and £1m [41]. These facilities mainly run on gas, costing £8-10 per tonne of SFS (based on UK energy costs in 2021). It was estimated that an average return on investment for a modern thermal reclamation could take more than five years.

Moreover, small to medium-sized foundries do not produce enough SFS to justify the operational and capital cost of modern thermal reclamation plants. Moreover, in the case of using the alkaline phenolic binder system, the sand must undergo additional pre-treatment with additives before reclamation. On the other hand, it is easier to recover the furan SFS with the thermal method, leading to an average recovery rate of 90%. The challenge with the furan binder system is the produced dust with high sulphur content, which is considered an environmental hazard. Below we have described the reclamation methods in further detail:

4.5.2 Mechanical reclamation

Mechanical reclamation is based on the principle of attrition. This method removes the surface deposits on the spent foundry sands by rubbing sand grains against each other or an external media such as an agate ball [126]. In order to separate the fine grains and remove the coatings, SFS is usually passed through sieves and cyclone separators [126].

Another method to reclaim SFS is through fluidised bed reactors, where SFS is reclaimed at different operating pressures [127]. Previous researchers have utilised this method for greensand and calcined greensands to investigate the impact of pre-calcination on the mechanical reclamation potential of SFS [127]. The results showed that prior calcination would improve the reclamation process.

4.5.3 Thermal reclamation

During the thermal reclamation, the SFS is heated to 700°C. This process burns the dead binder attached to the sand grains [128]. Although energy intensive, the thermal reclamation method is relatively efficient, especially for the core sand [129]. Most binding agents can be removed using this method, and the final reclaimed sand can be used to make moulds and cores in the foundry [130]. On the other hand, in the case of greensand, the thermal method is not the sole method required. While the heat converts the active clay into dead binder/oolitic deposits, the dead binder on the surface of the sand cannot be removed by thermal reclamation. A mechanical method is required for this purpose. Therefore, to reclaim mixed sands, both methods are necessary [131]. Due to the high cost of reclaiming greensand, the Cast Metals Federation (CMF) now suggests replacing thermal reclamation with a repeated mechanical scrub instead. Such types of system were previously set up at the Eurac facility.

According to Siddiqui *et al.* [132], SFS contains around 10% to 18% of loosely bound clay. The primary aim of any reclamation method is to decrease the dead clay content to less than 0.2%, which is suitable for making cores and moulds [133, 134]. Besides the dead clay content, other essential features of reclaimed sand are grain fineness number (GFN), loss on ignition (LOI), permeability, compressive strength, and acid demand value (ADV). [131]

5. Summary and conclusions

Currently, only about 25% of spent foundry sand (SFS) is reused and used for limited applications worldwide, mainly by the cement industry.[135] Accordingly, about 75%, according to some literature, of SFS is landfilled[136]. There is still a large potential for research research into the recycling of SFS.[137] This review focused on the various possible applications of spent foundry sand in the foundation industry. The potential technical routes and economics of applying SFS an alternative silicon raw material in foundation industries, such as cement, ceramics, glass and more widely in the construction industry, over the use of only natural sand and other raw materials, were identified. A number of challenges and potential future research directions are also presented and the following issues have been identified:

1. There is a lack of a unified standard for evaluating SFS.
2. Current studies on SFS reusage are mostly concentrated on independent case studies. However, there is a lack of multi-faceted comprehensive analysis that combines technology, economics, and the environment.
3. Previous studies on the impact of spent foundry sand on materials performance lack comprehensive research, and the performance characterization in individual cases is partial or lacks comprehensive testing.
4. Spent foundry sand is a by-product for some foundries as they meet specific current conditions, but for others, under UK legislation, they are required to classify their spent foundry sand as waste. This means that those foundries have to comply with additional regulations regarding the disposal and treatment of the spent sand, which can result in higher costs and administrative burdens. As a result, there is a need for greater clarity and consistency in the regulations governing spent foundry sand to help reduce the compliance burden for foundries while still ensuring that environmental standards are met.

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