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Waste Streams of the Foundry Industry and Approaches to Minimize Their Environmental Impact

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Abstract

The foundry industry is an integral part of the engineering industry, assisting in making machine parts and structural components. It is energy intensive and produces enormous quantities of waste, which is emitted into the atmosphere and into the waterbodies and landfills. In this study, current casting processes available and their waste streams are examined together with their long-term impact on society and the environment. Ways of improving material utilisation, lessening environmental impact and achieving compliance with pollution standards through analysis of available technology and processes and raw materials. A cost-benefit analysis of continuous improvements in casting environments and alternative manufacturing methods is conducted.

Keywords
Foundry, Waste and emissions, Environmental impact, Recycling

1. Introduction
The foundry industry is important in the growth of any industrialising nation, contributing parts and components of aerospace and defence, oil & gas, mechanical engineering, and automotive industries (Grand View Research 2024; Ramaprasad & Srinivasan 2012). Foundries are diverse materials such as cast iron, ductile iron, steel, copper alloys, aluminium, magnesium, and zinc alloys (Twarog 1993; Tiedje et al. 2010; Merta et al. 2021; Ramaprasad & Srinivasan 2012). It supports the downstream industry and provides employment (50th Census of World Casting Production 2016). A study in South Africa, 170 operating foundries employed about 9,500 people by 2015 with an output of 430,000 metric tons (South African Institute of Foundrymen 2017; Davies 2015). It is reported that in 2023, the global die casting market size was estimated at USD 77.99 billion, growing to USD 82.86 billion in 2024, and projected to reach USD 112.14 billion by 2029 with an annual growth forecast to grow at 6.24% per year (Mordor Intelligence 2024). The global investment casting market, which dominates aerospace & defence components, was valued at USD 16.55 billion in 2022 and is expected to grow by 5.0% from 2023 to 2030 (Grand View Research, 2024). Major foundry producers are in North America, Europe, Asia, and South America (Grand View Research 2024).

A study of the foundry industry in South Africa showed that there are 114 (66%) in Gauteng, 27 in KwaZulu-Natal, 14 in Cape Town, and eight in the Eastern Cape. The majority in Gauteng contributes 34.7% of the gross domestic product (GDP) in South Africa (Iloh et al. 2019). However, the small and medium-sized foundry sector has seen a total of 25 foundries closing since 2010, shedding 1,600 jobs (South African Institute of Foundrymen 2017). Foundries lack manufacturing economies of scale, with outdated infrastructure for capital equipment parts, and lack capital investment to achieve capacity utilisation (South African Institute of Foundrymen 2017). Raw material made up 40% of the cost of an aluminium casting scrap was a key cost driver in producing castings (Fubbs 2015). The output in

2013 of 375 240 tons was down from 660 400 tons in 2007, or 43% lower (Fubbsn2015). Sustainability is important in the foundry industry (Beyerstedt 2021; Foundry-Planet 2022). In addition to sourcing affordable raw materials and energy, adoption of best manufacturing practices particularly waste management will contribute to sustainable manufacturing (Fubbs 2015; Iloh et al. 2019).

The foundry industry faces environmental constraints due to requirements for waste management and hazardous waste disposal, and compliance with minimum requirements for the handling, classification, and disposal of hazardous waste (EI-Mohamadi, 2012; Iloh et al. 2019). The foundry industry consumes over 100 million tonnes of sand each year, without recycling the waste sand generated by its processes (Foundry-Planet 2022). The strength and integrity of a sand casting mould is ensured by mixing the sand with a binding agent, often resins, therefore preventing mould collapse during casting (Jain 1992; Merta et al. 2021; Tiedje, et al. 2010). The heat of the molten metal causes the binding agents to adhere to the surface of the sand grains, reducing their reusability (Foundry-Planet 2022; Merta et al. 2021). Most of the sand generated by moulding processes is not recycled, causing a waste disposal problem (EI-Mohamadi 2012). Most common of the sand is replaced with virgin sand while the used contaminated sand is disposed of in landfills (EI-Mohamadi 2012; GreenCape 2023). Metal casting is a recycle-intensive industry and presents environmental and health hazards due to emission of solid, liquid, and volatile wastes (Baloyi & Thethwayo 2019; Adegoloye et al. 2015; Foundry-Planet 2022). To comply with environmental and workplace regulations costs are incurred to limit emissions (Twarog, 1993; Banerjee 2024).

Different emissions from foundries include (a) sand system waste (b) mould and pouring emissions (c) furnace emissions (d) shake-out emissions (e) storm water runoff (f) unfired core waste (g) core room emissions (h) cleaning room dust (i) shotblast and baghouse dust (j) emission control water (Twarog 1993; Banerjee 2024; Beyerstedt 2021). A study of the South African foundry industry reported that around 3000 tonnes of WFS is discarded annually by a single foundry in Gauteng, totalling 342,000 tonnes being discarded annually in Gauteng alone (Iloh , et al., 2019). The foundry industry waste discharges large volume is estimated to comprise about 250,000 tonnes of silica and 25,000 tonnes of chromite sands (Nyembwe et al. 2018). In the Western Cape there are six foundries together producing 75 000 - 80 000 tonnes of WFS per year (GreenCape 2023). In the United States it is reported that the annual generation of foundry waste, dust and spent foundry sand about 9 to 13.6 million metric tonnes (US FHA 2016). Challenges posed by foundry sand in many countries include lack of specific regulation, high disposal cost, lack of framework to deal with WFS (EI-Mohamadi 2012). In this paper origins of waste, waste streams of different foundry operations and their impact on the environment and proposes measures to reduce waste in foundry practice.

1.1 Objectives

The objectives of this study are to:

- identify the different wastes produced in foundry operation with emphasis on sand casting operations.
- identify the short- and long-term effects of the waste streams to the environment.
- identify ways to minimize waste production and emissions during foundry operations.
- find alternative ways of handling waste through recycling and reuse to minimize environmental impact

2. Literature Review

Casting fabricates metallic solid parts into their net or near-net shape from molten materials using moulds or dies (Mohamadi 2012; Swift & Booker 2003; Bennett 2022). Its steps involve mould making, melting, pouring, cooling and extraction (Swift & Booker 2003; Bennett 2022; Grand View Research 2024). Early artisanal foundries worked ith brass and bronze in sand casting but today it casts different materials including a wide range of ferrous and non-ferrous alloys for machine parts and other industrial products (Grand View Research 2024). Modern foundries face high melting temperature materials, safety concerns, complexity of designs, diverse products, and large castings (50th Census of World Casting Production 2016). Selection of casting method depends on the type of material, casting design complexity, production run volume, dimensional tolerance, and surface finish (Swift & Booker 2003; Jain 1992; Kopeliovich 2023; Bennett 2022). Casting methods use permanent, semi-permanent and expandable moulds (Reliance Foundry Co. Ltd. 2023). Expandable moulds such as sand moulds are used for high temperature castings e.g., ferrous metals while permanent ones are reusable and used for non-ferrous metals such zinc, aluminium, magnesium, tin, or copper (Shenzhen Rapid Direct Co. Ltd 2022; Bennett 2022). Figure 1 is a summary of casting methods and mould types.

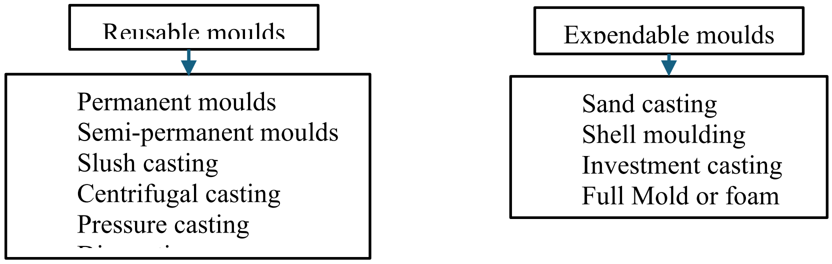

Figure 1. Different mould types and casting methods

Sand casting is either green sand casting using a cheap, having low strength and high moisture content or dry sand casting where a mould is oven cure to dry it (Banerjee 2024; Bennett 2022). Foundry sands are classified into two main categories namely green moulding sand (GMS), bonded with clay, and chemically bonded sand (CBS), bonded with resin (GreenCape 2023; EI-Mohamadi 2012). Skin-drying applies heat to dry the mould to a certain depth and is used in the casting of steels (Swift & Booker 2003; Bennett 2022). Centrifugal casting achieves solidification and consolidation of the molten metal by use of a rotational centrifugal force rotating the die forcing the molten metal to stick to the sides of the die (Poli 2001; Banerjee 2024). Die casting gravity uses a permanent mould and depending on the pressure, is either, low-pressure die casting for large and simple parts production and the high-pressure die casting for complex geometries that require high precision (Ramaprasad & Srinivasan 2012; Otarawanna & Dahle 2011).

Liquid forging or squeeze casting is a hybrid metal forming process that merges permanent mould casting and die forging in a single step (Murali & Yong 2010). During squeeze casting specific amount of molten metal alloy injected into a die is pressured to shape it (Murali & Yong 2010). Continuous casting is a vertical casting process creating semi-continuous casting mass produces metal profiles with a constant cross-section like billets, ingots, and bars applied in steel and nonferrous alloy production (Poli 2001; Kopeliovich 2023; Louhenkilpi 2014). Shell moulding is similar to the sand casting process but uses a hardened shell of heat treated and hardened sand mixed with a resin forms the mould cavity instead of a flask of sand (Jones & Yuan 2003). Vacuum casting occurs under vacuum pressure of 100 bar or less to exhaust gas from the mould cavity which allows the molten metal to be poured while bubbles, air pockets and gas entrapment is eliminated (Uchida 2009). Slush casting is a permanent moulding process to create a hollow casting or hollow cast by pouring molten material into the mould and allowed to cool and remaining liquid being poured out forming a shell of material in the mould (Otarawanna & Dahle 2011). Lost wax process creates a pattern of wax which is coated with a refractory ceramic by dipping, coating, spraying, or brushing. Then, the molten metal is poured into the mould to form the desired product (Voxeljet AG 2020).

2.1 Melting practice for metal casting

In any casting process moulding and melting controls the quality of the casting (Piwonka, 1998; Banerjee 2024). During melting the molten metal is refined and treated to change its composition and properties (Banerjee 2024). The type of alloy being melted, the power cost, and environmental regulations determine melting technology (Piwonka, 1998; Brightstar Aluminium Machinery Ltd 2017). Basic steps of melting are furnace charging with the metal alloys, scrap and additives such as carbon, and flux followed by melting of the charge in a closed furnace before back charging or addition of more metal and alloys, and finally, refining and treating (Banerjee 2024; Ibrahim et al. 2016). During treating and refining, the alloy's chemical composition is adjusted to specifications (Banerjee 2024). Casting processes involves melting of the prepared scrap in a furnace. The most basic furnace is a cupola steel melting furnace which is dome-shaped and built from sedimentary rocks, lined with clay and refractory bricks for heat and abrasion protection (Banerjee 2024; Ibrahim, et al. 2016). Another type of furnace is the crucible forging furnaces made from moulded refractory ceramic materials used for melting different metals.

They vary in size and are cup-shaped or form large kiln furnaces, the inside of which a metal alloy charge and additives are placed before a heat source fires it from underneath (Amelt Corporation Canada 2020). Induction forging furnaces fired electrically are now dominate furnaces especially for steel production. They use alternating electric currents and induction technology; they melt the alloy charge at rapidly reaching up to 1370ºC temperatures. An induction heating coil surrounding a crucible generates the heat energy (Amelt Corporation Canada 2020). Electric arc furnace is another furnace that uses electrodes dipped in the metal charge to generate the heat through arcing which effects melting. Carbon electrodes are often used to charge the material directly until it melts. Electric arc furnaces are used in steel recycling and provide for easy starting and stopping the furnace and batch processing, even though they have high energy consumption (Amelt Corporation Canada 2020). Furnace selection determine a foundry's energy efficiency, waste and reclaiming of the foundry operation (Amelt Corporation Canada 2020; Banerjee 2024; Jiang 2024).

2.2 Foundry operations and waste generation

Different foundry operations produce waste which depend on the processes (Bennett 2022; EI-Mohamadi 2012). Energy consumption and material loss are important cost factors in foundries (Bennett 2022; Beyerstedt 2021; Jiang 2024). Materials used during moulding process such as sand present environmental pollution during its disposal (EI-Mohamadi 2012). Gaseous pollutants such as carbon and sulphur dioxide are produced during the melting and pouring processes (Banerjee 2024; Beyerstedt 2021; Ibrahim et al. 2016) and solid waste such as slag during melting process (Beyerstedt 2021; Adegoloye et al. 2015; Gurumoorthy & Arunachalam 2016). During melting material loss is due to unintended reactions due to oxidation leading to loss of the metal constituent elements such as silicon and carbon (Ibrahim et al. 2016; Banerjee 2024). This leads to a casting whose composition is out of specifications leading to scrapping (Beyerstedt 2021; Jiang 2024).

2.2.1 Oxidation loss during melting

By products of the clean charge material melting process can reduce the metallurgical quality of the metal produced (Beyerstedt 2021). Oxidation, volatilization and the interaction of furnace wall and refining agent often result in burning loss which leads to irrecoverable metal loss (Beyerstedt 2021). Metal in burning loss and residue is collectively referred to as melting loss in factory cost accounting terms (Jiang 2024). Such losses occur in the tuyere area of a Cupola furnace where iron oxide is formed at extremely high temperature causing a portion of the freshly formed iron oxide, together with molten iron and coke ash (Tech Quality Pedia 2021). The formed vaporized gas spreads throughout the furnace before cooling, and condensing into a liquid, contaminating the upper cupola with iron oxide (Mechnical Jungle 2022). The metal oxidation produced in the process of producing, removing, transferring, storing, and remelting. Slag contained in the waste is calculated as (Jiang 2024):

$$Burning\ loss = \frac{(Metal\ fed - Recycled\ output)}{Metal\ fed} \times 100\%$$

recycled output: refers to the metal part that can be returned to the furnace. In steel production, a reduction in the quantity of slag is observed after the introduction of silicon to the charges (Banerjee 2024). Slag causes some heat lost from the melting process. When less slag is produced, the charge melting rate increases therefore increasing in time of production and reducing heating cost (Brand & Roesler 2015; Adegoloye et al. 2015). Figure 2 shows the different cast iron foundry steps which results in the production of waste and emissions (Stefana et al. 2019).

2.2.2 Carbon and silicon loss through oxidation

Carbon and silicon are often lost during steel and cast iron production through oxidation. This affects the carbon equivalent value (CEV) of the alloy produced (Omole, 2015). CEV affects alloy fluidity of molten metal and improves mechanical properties of cast products (Omole 2015). To remedy this loss, graphite and ferrosilicon were added to the charge to adjust the composition (Omole, 2015; Tiedje , 2010). Carbon oxidizes more than silicon and Inoculation of the melt compensates for the loss of silicon in the furnace which excessive heating of the melt at tapping temperature is detrimental leading to the carbon and silicon loss (Jain 1992). CEV is defined as :

$$CEV = \%C + (\%Si + \%P)/3$$

Composition losses due to oxidation are calculated from the difference between carbon and silicon prepared in the charge to the value obtained in the casting after test (Jain 1992; Tiedje 2010). Graphite as re-carburizer is added into the charge in the furnace to compensate for carbon loss and to balance the carbon equivalent (Omole 2015; Tiedje , 2010). More time given to the melt during super heating in the furnace and time to complete the discharge of the molten metal in the furnace need to be controlled, in order to reduce the percentage elemental loss in the casting (Omole 2015).

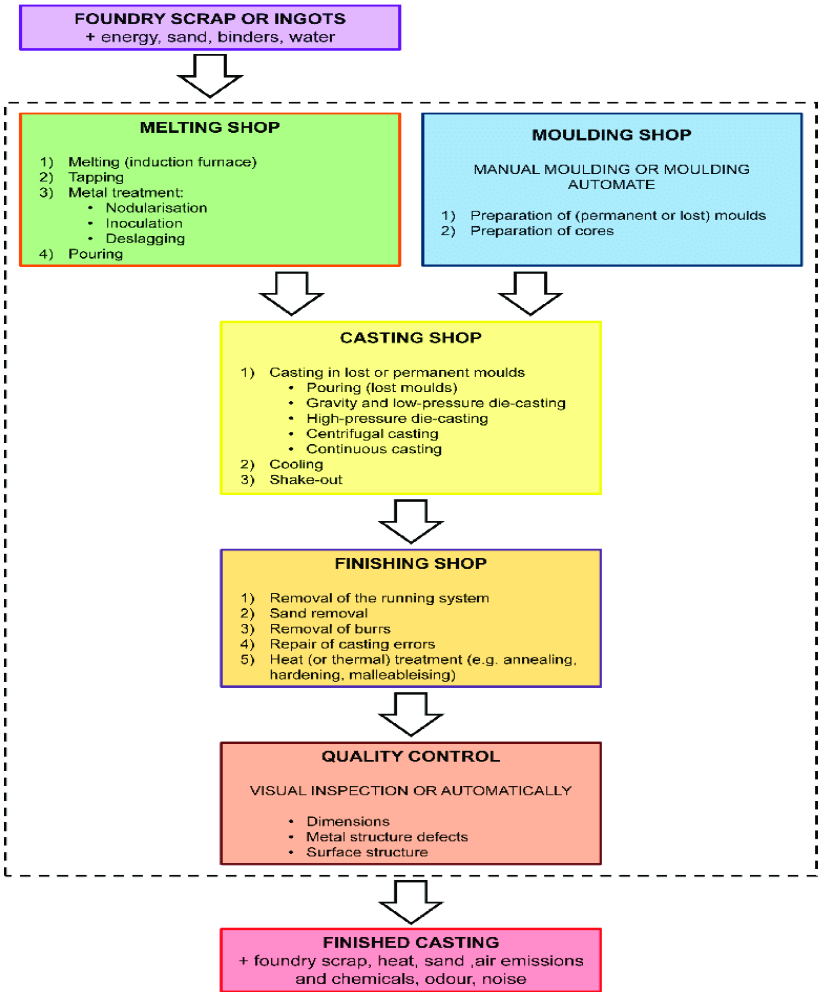

Figure 2. (a) Die casting process flow chart (Stefana, et al., 2019)

3. Research Methods

This research reviews different foundry processes and their waste streams. From historical records waste generated from foundry operations are documented with focus on less industrialized countries. The environmental impact of waste and operations of the foundries is investigated. Methods of mitigating waste are proposed together with alternative uses of foundry waste products.

4. Discussion

In many old foundries for steel alloys, coke, and limestone are filled the characteristic high and cylindrically shaped dome cupola furnaces then melted (Amelt Corporation Canada 2020). Although such furnace produces large quantities of steel, often running for years at a time they are inefficient and are being replaced with the more efficient induction furnace technology (Amelt Corporation Canada 2020). Cupola furnaces suffer from heat loss due to other convection and convection through their walls, the slag and through flue gases. Some energy is also lost through radiation when the furnace door is opened (Ibrahim et al. 2016). In order to preventing burning loss during melting the design of the furnace, melting practice and temperature control are important (Banerjee 2024). It is important to select appropriate regulation of temperature during the heating process to reduce energy waste. Temperature control during melting ensures heating rate proceeds rapidly and precaution must be taken not to overheat the melt by regulating the heat source (Brightstar Aluminium Machinery Ltd 2017). An appropriate design of furnace ensures rapid charging and strong heating reduce energy consumption (Ibrahim, et al. 2016). Adopt a round shape with top charging to speed up heating and melting. An electromagnetic inductor on the bottom of the furnace reduces power consumption (Banerjee, 2024; Amelt Corporation Canada 2020). Natural gas or LPG can be used in melting as opposed to coal to ensure sustainable production (Banerjee 2024). Methods of temperature control include controlling oxidation gases using micro gas which also ensure minimal oxidation burning losses and hydrogen pick up by the molten metal (Ibrahim, et al. 2016). When loading the furnace, charge material that oxidizes easily should be stacked at the furnace bottom (Banerjee, 2024). Alternatively, such material can be loaded after the less oxidizing one is melted or later in the melting process (Brightstar Aluminium Machinery Ltd 2017).The surface of the furnace can also be protected by flux or a covering agent to protect the melt below. The active element in the flux above will burn first (Brightstar Aluminium Machinery Ltd 2017).

During melting heat is lost by a furnace through flue gases (Ibrahim, et al. 2016; Beyerstedt 2021). Charging of a furnace must work in counter flow principle whereby charges flow in opposite to the flow of heat, maximising heat absorption by charges before flue gas escape (Ibrahim et al. 2016). Minimisation and optimisation of energy consumption is required in foundry operations because energy is a large percentage of operational cost (Amelt Corporation Canada 2020; Banerjee 2024; Ibrahim et al. 2016). When induction furnaces are used, nonproductive energy cost determined by multiplying the cost of power per kilowatt-hr by process efficiency by furnace running idle time can be a considerable loss (Pinney 2022; Donsbach et al. 2024). An optimised and well-designed induction furnace with a good melting coil and refractory system can achieve up to 85% efficiency (Pinney 2022; Donsbach et al. 2024).

Research on a modern 5000-kilowatt induction furnace using a solid-state AC-DC rectifier/DC-AC inverter can achieve power efficiencies of about 97% (Pinney 2022). Problem-solving to improve power efficiency includes heat loss calculation of the existing bus bar to determine baseline operating system efficiency (Donsbach et al. 2024). To reduce power losses and reduce consumption of an induction furnace, it is important for the busbar to be spaced properly between adjacent phases, ensuring an increase in its copper cross section to improve surface area while the water-cooling the bus must be well designed (Pinney 2022). Other energy conservation measures when using an induction furnace is the use of well-prepared scrap which is pre-heated, minimising open cover times, good refractory practice and efficient charging, alloying, and tapping (Pinney 2022; Donsbach et al.2024).

4.1 Binder processes

There are three main classes of binder systems used in core and mould production namely heat activated, no bake, and cold box (Twarog 1993; Tiedje, et al. 2010; Merta, et al. 2021). Binder processes are initiated by blowing a resin and a sand mixture into a core box (Merta et al. 2021). Hot box binders include phenolic resins, furan resins, with urea formaldehyde added to improve the tensile strength (Tiedje et al. 2010; Merta et al. 2021). The warm box process utilises a lower curing temperature and uses catalyst is copper salts or sulfonic acids (Merta et al. 2021). Hot-box binders decompose during the casting process and emit pollutants such as benzene, toluene, hydrogen cyanide and formaldehyde (Twarog 1993; Tiedje et al. 2010). The shell moulding process is rich in phenol which is emitted during cooling. Similarly in operating foundries chemicals are emitted from cooling moulds (Twarog 1993).Adding core oil involves the mixing of core oil and a water activated cereal which is blown into a mould and blended with sand (Merta, et al. 2021). The core is heated releasing amines, hydrogen sulphide, toluene, formaldehyde among other emissions (Twarog 1993; Tiedje et al. 2010). No bake or self-setting binders are either acid catalysed, or ester cured (Merta, et al. 2021). Binders used in this process include furan acid, phenolic acid, phenolic/ester, silicate/ester, phenolic urethane, and alkyd urethane systems (Twarog 1993; Tiedje et al. 2010). Alkyd urethane is composed of lead, cobalt, naphthalene, 1,2,4 trimethylbenzene, and methylene phenylene isocyanate which are potentially sources of hazardous air pollutants (Twarog 1993; Tiedje et al. 2010).

4.2 Sand waste from foundries

Foundry operations produce on average one to two tonnes of waste foundry sand per tonne of metal moulded (GreenCape 2023). Three foundry waste sand streams are moulding, shakeout or casing knock out, shot blasting, and dust from handling (Nyembwe et al. 2018). Waste or spent foundry sand is composed of silica sand, coated with a thin film of burnt carbon, residual binder with bentonite, sea coal or, resins and dust (US FHA, 2016). After use foundry sand is crushed and separated to an average grain size ranging from 0.05 to 2mm (GreenCape 2023). The binder and type of metal cast, affect the pH of waste foundry sand which ranges from 4 to 8 and in some instances is corrosive to metals (Johnson 1981). Resin knock sand possess coarser grains and less clay, sulphate, and organic content than green sand (Nyembwe et al. 2018).

4.2.1 Monitoring and environmental assessment of foundry sands

There is lack of measurement of waste from foundries and continuous monitoring. The type of test can charecterised material as toxic and harmless. Emission of foundries can be done using leaching test includes the elements Al, Fe, and Mn. South Africa is applying the leaching test, toxicity characteristic leaching procedure (TCLP) to evaluate leaching from inorganic materials. Tests on foundry sands in the US, among other countries, declassified foundry sand as a hazardous material and allowed it to be suitable as a natural sand alternative (EI-Mohamadi, 2012). Additionally, dissimilar metal moulding facilities utilize varied particle sizes for foundry sands, e.g., coarser sands for steel facilities and finer sands for non-ferrous facilities (Iloh et al. 2019). Waste disposal is a key challenge in disposal of foundry sands. In South Africa, the average landfilling tipping fees of foundry by-products due to space shortages are about US $34 per ton inclusive of storage, transportation, and labour cost, while, in the United Kingdom, it is about US $4.3 (Mohamadi 2012). Since the ferrous and non-ferrous foundries produce a voluminous quantity of WFS, there is a concern over the existing landfill sites which are also under pressure due to reducing life span on the account of ever-increasing waste generated annually (EI-Mohamadi 2012). Grains of waste foundry sand are coated with films of burnt carbon, residual binder comprising of resins and other chemicals and contain dust, and some studies have shown that it is corrosive to metals (Johnson, 1981; MNR 1992). In addition, the presence of phenols in foundry sand raises worries that the infiltration of precipitation over stockpiles might accumulate leachable segments, resulting in the releases of phenol into ground or surface water supplies (Johnson 1981; Iloh et al. 2019). WFS stockpiles and origins must be examined to evaluate the need to establish control over potential phenol discharges (EI-Mohamadi, 2012; Foundry-Planet 2022).

4.2.2 Finding uses of foundry waste

The grain structure of waste foundry sand is uniformly sized and when mixed with binders, metal types, binding systems, additives create moulds for ferrous and nonferrous metal castings after which it is discarded (Siddique et al. 2010; Davies 2015). When disposed in landfills, leachates that drains or 'leaches' from the landfill willing contain contaminants from the sand (Siddique et al. 2010; Iloh et al. 2019; Davies, 2015). Leachates vary in composition depending on age of the landfill and waste type (Siddique et al., 2010). In US Approximately 10 million tons of spent foundry sands are produced annually; only 26 percent is beneficially used (US Environmental Protection Agency , 2023). US EPA supports the beneficial use of silica-based spent foundry sands specifically from iron, steel, and aluminium foundries. Examples of uses include manufactured soils, soil-less potting media, and roadway construction as subbase, (US Environmental Protection Agency 2023).

Production of manufactured soils involves blending soil, its components and soil-like material. Manufactured soil is used in horticulture, green houses, raised grow beds, landscaping and for degraded site restoration (US Environmental Protection Agency 2023; Siddique, et al. 2010). Using spent foundry sand in asphalt, and cement production. Alternative use in construction promotes sustainability saving energy, water and minimising carbon emissions that could otherwise been used in procuring alternative sands (US Environmental Protection Agency , 2023). Other applications include construction of embankments, concrete mixes and for soil amendments for horticulture (Siddique et al. 2010). Used foundry sand are high quality silica sand and after use in ferrous and nonferrous metal casting it contains iron and other metals content which require treatment with acid to enrich silica before use in concretes (Gurumoorthy & Arunachalam 2016). Waste from dust streams have finer grain size, making its recycling practical in cement manufacturing (Nyembwe et al. 2018). Shot blast sand has high density, low silica content, and high metallic debris content and is not suitable for recycling applications (Nyembwe et al. 2018).

4.2.3 Recycling foundry sand

Foundry sand can be reconditioned and recycled for use by the foundry itself in its moulding operations. However, small scale foundries, often lack the resources and the equipment reclaim used sand. This is due to the cost of installing specialised reclamation equipment and return on investment does not justify effort when volumes are low (GreenCape, 2023). An example of waste foundry sand recycling is in Finland where a company Finn Recycling's regeneration solution extends the service life of foundry sand and thus reduces the use of virgin sand, and the amount of waste sand and greenhouse gas emissions generated by foundry processes (Foundry-Planet 2022). Mechanical recycling typically achieves a 70–90% recycling rate for used sand. In addition, the ten-year cumulative emissions reduction potential of a single reclaimer is approximately 2.8 kt CO_2eq. (Foundry-Planet 2022).

4.2.4 Concrete brickmaking

The manufacturing of concrete bricks requires an aggregate material comprising a mix of up to 30% fine and the balance being coarse sand (GreenCape 2023). When WFS is used it must have low clay (bentonite) content of less than 2% to have high strength perform better than those with a high content. WFS imparts a dark colour to concrete bricks which is preferred by builders and consumers. WFS is screened for contaminants such as metal particles since they may oxidise and compromise brick strength (GreenCape 2023). Recycling of WFS can be done at the foundry site or off site and may require purchase of specialised separation equipment.

4.2.1 Foundry slag

Foundry slags (FS) are waste materials generated by metal casting processes at metal foundries (Adegoloye, et al., 2015; Motz & Geiseler 2001). Four different ferrous slag families can be identified: i) blast furnace slag (BF) also called iron slag, air-cooled (ABS) or granulated (GBS); ii) basic oxygen furnace slag (BOS); iii) electric arc furnace slag from carbon (EAF C) or stainless/high alloy steel production (EAF S); and iv) steelmaking slag (SMS) (Kvočka, et al. 2022; European Slag Association, 2017). Usually, BF and ABS are summarized as "blast furnace slag," while BOS, EAF C, EAF S and SMS are called "steel slags" (Adegoloye et al. 2015; Kvočka et al. 2022). Foundry slag, obtained by induction, is treated as waste from the ferrous industry and is disposed in landfills (Brand & Roesler, 2015; Motz & Geiseler, 2001).The use of these stainless steel slags was very limited because of their high chromium content unless the leachable chromium is reduced (Adegoloye et al. 2015). steel slag can contain high contents of free calcium and magnesium oxides, which expand during the hydration process and usually lead to cracking in confined applications (Brand & Roesler 2015).

Regarding alkali-silica reactions, resistance to sulphates and susceptibility to corrosion, which sometimes, in practice, can make some slags in concrete impracticable (Kvočka et al. 2022). The use of BF slag as a partial substitute of aggregate in concrete (Baricová et al. 2010; Bodor et al. 2016; Kawamura et al. 1983; Krishna Rao et al.2015; Motz and Geiseler 2001) or in the manufacturing of cement as a partial substitute of Portland cement clinker (Miyazawa et al. 2014, Özbay et al. 2016) is a well-known practice. Reduction of the environmental impact and carbon footprint of concrete production can be achieved by adopting green concretes, composed of different recycled waste materials (Kvočka, et al. 2022). An example is EAF slag aggregates derived from carbon steel manufacture which possess mechanical strength and high specific density of about 3.6 due to their iron oxide content (Adegoloye et al.2015). This steel slag, according to research is suitable in concrete, as fine or/and coarse aggregate replacement (Kvočka et al. 2022; Santamaría, et al. 2022)and also for cement production and as a supplementary cementitious material for concrete production namely BOS (Santamaría et al.2022; European Slag Association 2017).

4.2.2 Reclaiming of furnace refractories

Refractory grog i.e., used refractory bricks and monolithics from furnaces are a waste product (Schutte 2010). Refractory materials containing copper, magnesite, chrome, and bauxite cause environmental impacts. Chromium (VI) can cause cancer when disposed of into the environment (Baloyi & Thethwayo 2019). Refractories based on bauxite for the Chinese aluminium industry are becoming expensive due to its demand in other products. As a result, andalusite is now being used as a replacement raw material. Changes in the industry such as increasing import taxes, price increases of virgin materials and shipping costs have caused a shift to the use of reclaimed refractory materials for the production of mainly monolithic refractory materials (Schutte 2010). Reclaimed refractory grogs can be used for producing monolithic refractory materials such as refractory bricks and monolithics based on chamotte, andalusite, bauxite, high alumina, silicon carbide, magnesia, magnesia-chrome, magnesia-spinel, magnesia-carbon, dolomite, and graphite/carbon (Schutte, 2010). Typical datasheet of a chamotte grog-based castable containing 46% Al_2O_3, 44% SiO_2 and 1% Fe_2O_3 that can also be used as a plaster material in the copper industry operating up to temperature of 1600ºC (Schutte 2010).

4.3 Adopting sustainable for the foundry industry

The foundry industry can adopt more sustainable manufacturing processes by adopting best practices such as using biodegradable binders for sand moulds, recyclable materials, and bio resins (Cast Products South Africa 2024). The use of virgin materials can be reduced by increasing recycling of scrap into the manufacturing process therefore reducing carbon footprint and cleaning the environment. Scrubbers and filters can be used to clean flue gases which closed loop water systems can be adopted to limit pollution of water bodies. Gradually sand casting can be replaced by cleaner manufacturing methods such as 3D printing and alternative casting processes (Cast Products South Africa 2024).

5. Conclusion

Metal casting processes are important part of engineering and manufacturing of capital goods such as machinery, vehicles, and other equipment. While delivering industrial benefits they are energy intensive, producing waste products that affect human health and land use. It is important to identify sources of losses of raw materials and energy during melting, pouring, and finishing. Melting and casting practice affects material utilisation and losses, quality of the casting and emits gases which pollute the workspace and environment. Strategies for pollution prevention such as waste handling, treatment through recycling, alternative uses such as construction and environmentally conscious disposal technologies can be applied to minimize impact of waste emanating from foundry processes. Mould used in casting process and materials used for furnace linings cause a considerable amount of waste that end up in the landfills. Finding uses of sand in construction, farming and reclaiming it can solve the foundry sand disposal problem. Furnace linings can be reused in other processes. Slag can be used in cement and paint pigments. By finding alternative uses of waste foundry sand will divert it from landfill which can the industry, society saving costs and reducing environmental impact. Companies using silica or other sands such as brick manufacturing and construction can use waste foundry sands as secondary raw material.

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