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The Impact of Iron Casting in Cupola Furnaces on the Environment †

Patrik Fedorko *, Alena Pribulová, Jozef Petrík, Peter Blaško and Peter Futáš

Faculty of Metallurgy, Technical University of Košice, 04200 Kosice, Slovakia; alena.pribulova@tuke.sk (A.P.); jozef.petrik@tuke.sk (J.P.); peter.blasko@tuke.sk (P.B.); peter.futas@tuke.sk (P.F.)

* Correspondence: patrik.fedorko@tuke.sk; Tel.: +421-55-602-3142

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Abstract: The production of iron castings in cupola furnaces is a significant industrial process that has a notable impact on the environment. This paper examines and describes the environmental impact of this process, specifically focusing on the generation, characterization, and utilization of waste materials through data analysis and collection. Approximately one hundred and two million metric tons of castings are produced worldwide each year, with approximately one ton of foundry waste generated for every ton of castings. The slag from this waste can amount to as much as 7.14 million metric tons annually. Most of the slag ends up in landfills, which is expensive and represents a waste of this potential secondary raw material. Therefore, it is necessary to find ways to utilize this waste in other processes or industrial sectors. Cupola slag, given its high phosphorus content, can be used as agricultural fertilizer or in the production of ceramic foam used in foundries as filters during casting. In the construction industry, slag can be used in the production of concrete as a partial substitute for fine aggregate. This concept not only mitigates the environmental impact of waste disposal, but also aligns with the circular economy concept, promoting resource efficiency.

Keywords: cupola furnace; cast iron; cupola furnace slag; concrete

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1. Introduction

The foundry industry is one of the key sectors in the global manufacturing process, as it provides essential components for various industrial sectors crucial for the development of global infrastructure, ranging from the engineering to automotive and aerospace industries, among others. Among the many materials produced in foundries, cast iron (especially grey and ductile cast iron) holds a prominent position due to its exceptional mechanical and foundry properties, universal applicability, and cost-effectiveness. Ductile cast iron has gained widespread popularity in technical applications, where strength, toughness, and good machinability are crucial. Grey cast iron is known for its excellent foundry properties and its ability to effectively dampen vibrations and dissipate heat. The traditional method of producing cast iron using cupola furnaces has been the foundation of foundry processes for centuries. The charge is loaded into a cupola furnace in layers through the top opening and consists of pig iron, alloying additives, and limestone, with heat generated by the combustion of coke, which also serves as a carbon source.

As the environmental sustainability concerns intensify, it is essential to thoroughly explore the options for reducing the environmental impact of cupola furnaces.

According to the *Modern Casting* magazine (data from 2021), approximately 102 million metric tons of castings are produced globally each year (Figure 1), with most castings being made from gray iron (43.8 million metric tons) and ductile iron (24.8 million metric tons). The countries belonging to the European Foundry Association (CAEF) produce approximately 16.8 million tons of castings annually, representing 16.5% of global production. The

World Foundry Organization (WFO) states that for every one ton of castings produced, there is one ton of waste, which, according to the authors [1], has the following composition:

- Used foundry sand: 65–90%;
- Used refractory materials: 2–10%;
- Slag from melting: 1–7%;
- Dust and sludge: 2–6%;
- Other waste: 1–5%.

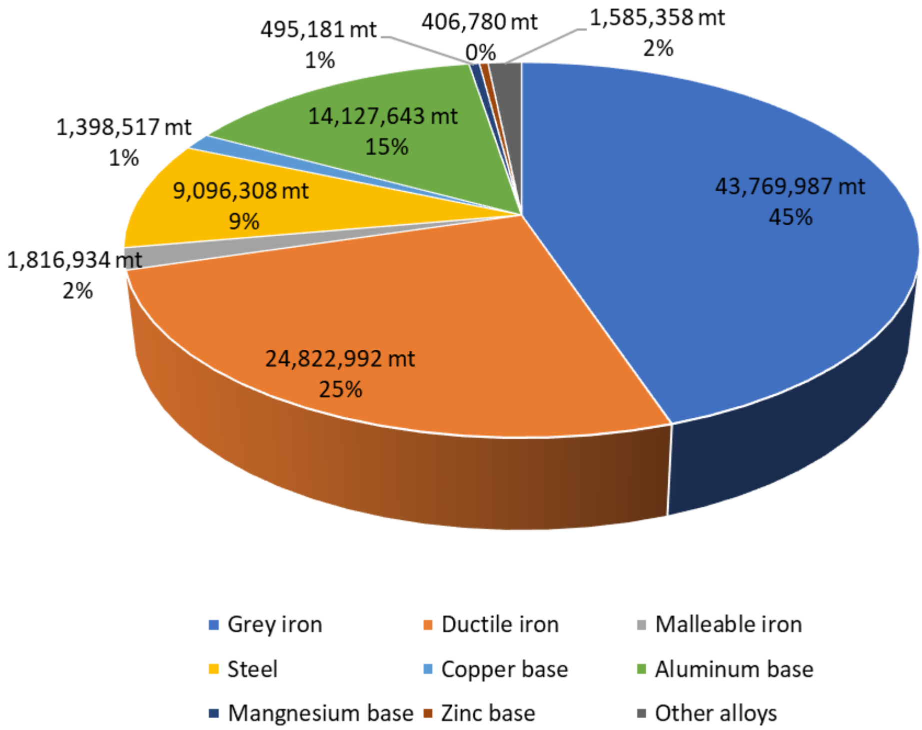

Figure 1. Material composition of castings (2021 data) [2].

Most of this waste ends up in landfills, causing not only the exacerbation of environmental issues, but also a waste of potential resources. Therefore, industrial enterprises and researchers are exploring and developing methods to transform foundry waste into valuable secondary raw materials. This paper will focus on cupola furnace slag.

2. Cupola Furnace Slag

This is a by-product of the cast iron production process in a cupola furnace, and, according to the authors [3], several factors influence its formation:

- Impurities in the pig iron charge—remnants of molding mixtures and iron oxides.
- Coke ash—metallurgical coke contains 10–13.5% ash, which contains SiO_2 (46%), Al_2O_3 (39%), Fe_2O_3 (6%), and CaO (4%).
- Refractory lining—SiO_2 and Al_2O_3.
- Metal oxides formed during melting—MnO and FeO.
- Sulfides—the result of sulfur transfer from coke to slag.
- Phosphides—formed during melting.
- Slag-forming additives.

The amount of slag produced in the cupola furnace is 5–10% of the metal's weight. Slag covers the melt, protecting it from the furnace atmosphere, reducing the heat losses, contributing to heat transfer into the melt, and having a refining function.

Slag that is allowed to slowly cool in the open air forms a gray, crystalline material known as air-cooled slag (Figure 2A). When crushed, it makes an excellent substitute for gravel. Another way to treat cupola slag is to pour it into a large amount of water or quench it with a water jet. This process creates granulated slag (Figure 2B), which consists of small particles and has a glassy character.

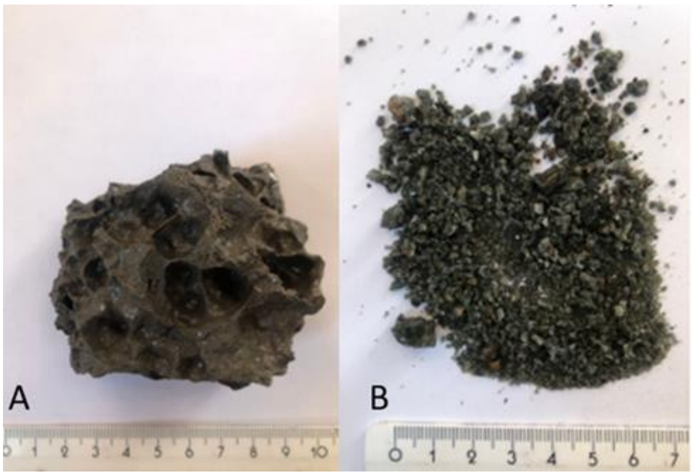

Figure 2. Cupola furnace slag: (**A**)—slowly cooled; (**B**)—granulated.

The chemical composition of slag depends directly on the composition of the charge materials and the melting process technology. The chemical composition influences the rate of crystallization during cooling (affecting porosity and crystal size), viscosity, and basicity (expressed as the ratio of basic to acidic oxides). These factors most significantly affect its potential utilization. The most abundant minerals in cupola slag are wollastonite ($CaO{\cdot}SiO_2$), fayalite ($2FeO{\cdot}SiO_2$), and other complex phases composed of SiO_2-Al_2O_3-CaO. Compared to blast furnace slag or steelmaking slag, the quantity of cupola slag on a global scale is much lower, but its quantity is still high. Therefore, its utilization in other industrial sectors is being sought.

Ceramic foams, due to their porous character and unique properties, find applications in foundries as filters for liquid metals, thermal insulation, or catalytic supports and gas filters. In a study [4], slag from cast iron melting for cast iron casting production was used to manufacture ceramic foam. The foam production mixture consisted of fine particles of Al_2O_3 (58%) and SiO_2 (48%), agents for creating pores of polymethylmethacrylate (PMMA), and water. The mixture of aluminum oxide and silicon oxide was gradually replaced by finely ground slag in amounts of 0, 25, 50, 75, and 100%. Ceramic samples were created using the split casting method, followed by drying and firing. The authors found that the density and pore diameter of the ceramic foam increased with the increasing content of slag in the mixtures. The ceramic foam with 100% slag content contained up to 55% more pores than the foam without any substitutions. This increase in porosity was attributed to the fact that slag contains various components that can spontaneously create pores. In terms of phase composition, the foam with 100% slag substitution contained wollastonite, $CaSiO_3$ (40.2%), and anorthite, $CaAl_2Si_2O_8$ (11.96%), which are components with a low coefficient of expansion and are resistant to thermal shock. Thanks to this, many authors consider ceramic foams with the addition of slag as highly promising materials to produce ceramic filters used for capturing inclusions during casting. The compressive strength increased with an increasing amount of slag, reaching a maximum value of 16 MPa, which was several times higher than the strength of the foam with zero slag addition.

Cupola slag is also a source of phosphorus and can be utilized similarly to phosphorus fertilizers, which are highly effective in agriculture. In another study [5], the authors examined various phosphorus-containing wastes, including cupola slag, as fertilizers. They compared the effectiveness of these wastes with common fertilizers like phosphate rock or superphosphate. The research was conducted with maize for two years in soils with pH levels of 4.7 and 6.6. The most crucial parameters observed were as follows: the phosphorus uptake efficiency, phosphorus concentration, and isotopically exchangeable phosphorus. The results they achieved showed that in neutral soil, cupola slag has a similar effect to superphosphate.

Experimental Materials and Methods

Due to its characteristics, cupola slag has the potential for use in the construction industry in concrete production. The substitution of fine aggregate with ground cupola slag was also carried out at the Institute of Metallurgy, Faculty of Materials, Metallurgy, and Recycling at the Technical University of Košice. From concrete mixtures, in which ordinary quartz sand is commonly replaced with ground cupola slag in quantities of 0, 10, 15, 20, 25, and 40 wt. %, samples in the shape of cubes and prisms were prepared (Figure 3). All the mixtures contained approximately 16% cement (Type I 42.5 R) and 1.2 mL of plasticizing admixture (MC Power-Flow 2695). The amount of water for each mixture was adjusted to achieve the desired workability and consistency determined by the slump test method. The prepared samples were cured in molds for 24 h, and then submerged in water for 7 days. After the removal from water, they were left to air-cure for 22 days. After 30 days from casting, the samples underwent compressive strength and flexural strength testing.

Figure 3. Concrete cube and prism.

3. Results and Discussion

The results shown in Figure 4 indicate that even the 10% replacement of sand with cupola slag reduces the compressive strength of concrete by 8 MPa (the strength of the concrete without the addition of slag was 38 MPa). However, the Slovak Technical Standard STN EN 12390-3 [6] specifies a minimum compressive strength for concrete of a given class (C20/25) at 25 MPa, and all the samples with cupola slag meet this criterion. In the case of the flexural strength of samples with sand replacement by cupola slag, there was not a significant decrease in strength, as observed in the case of compressive strength. Cupola slag in concrete did not have a pronounced impact on the flexural strength of the concrete samples. The standard, which is set at 5 MPa in this case, was not met only by the sample with a 40% replacement. In both these cases (compressive strength and flexural strength), the lowest values were achieved with a 40% replacement, where a significant deterioration in the workability of the concrete mixture and increased water consumption to achieve optimal consistency were observed. As reported in published studies [7,8], a higher water content in concrete results in the reduced strength of hardened concrete, and impaired workability can lead to inadequate cement hydration. At the same time, these studies indicate that higher proportions of fine particles can improve the properties of concrete up to a certain content by filling the voids.

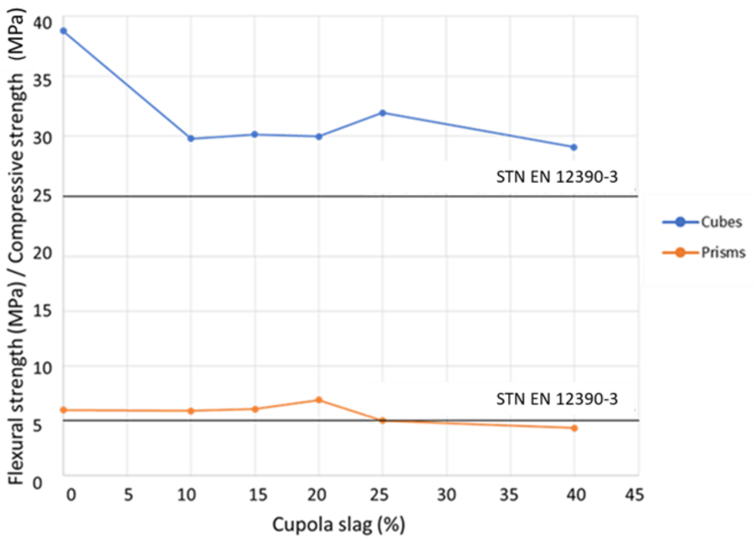

Figure 4. The impact of the quantity of cupola slag on compressive strength and flexural strength.

When using ground cupola slag in concrete mixtures, it is essential to mention a crucial property closely related to its utilization in construction, which is hydraulicity, as described in reference [3]. Hydraulicity is a concept associated with materials capable of hydraulic reactions with water. The main parameters influencing reactivity with water are chemical composition, the amount of vitreous phase (hydraulicity decreases with an increasing amount of the vitreous phase), alkalinity, and mineralogical composition. An increasing content of CaO, Al_2O_3, and MgO in the slag leads to increased hydraulicity, while an increasing SiO_2 content has the opposite effect. A lack of CaO can be compensated for by a higher Al_2O_3 content. The fineness of grinding also significantly influences slag hydraulicity, affecting its reactivity in concrete. The best results are achieved when the slag is finer than the cement. Consequently, hydraulicity can have a substantial impact on the ultimate strength properties of concrete samples.

4. Conclusions

The production of cast iron in cupola furnaces has a significant impact on the environment. Emissions, energy consumption, and the generation of waste during this industrial process contribute to environmental degradation, including an increased carbon footprint and potential concerns about the soil, water, and air qualities. Foundry waste from cast iron production can be transformed into valuable resources through proper practices. Ground cupola slag can be combined with PMMA using the split casting method to produce ceramic foam. In foundries, ceramic foam is used to filter the impurities from molten metal. Foam prepared in this way exhibits better strength properties than the traditionally manufactured ceramic foams, with a low coefficient of expansion and high resistance to thermal shock. The high phosphorus content in cupola slag allows for its use in agriculture as a phosphorus fertilizer, with results comparable to the commonly used superphosphate in neutral soil conditions. In concrete production, cupola slag can potentially serve as a partial substitute for fine aggregate. Concrete samples with up to 25% ground cupola slag as a sand replacement meet the Slovak technical standards.

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