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TECHNIQUES OF REUSE FOR SLAGS AND FLAKES FROM THE STEEL INDUSTRY: A CIRCULAR ECONOMY PERSPECTIVE *

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Abstract

The steel industry has always been characterized by the model of a linear economy as industrial waste was considered waste to be dumped in landfill sites. This principle is opposed to the circular economy model, defined as an economic system where companies that adopt it reuse waste materials coming from a production cycle in any subsequent production cycles. In this regard, waste from steel production is the subject of this paper: more in-depth, the reuse of flake obtained during the flaking of the billets, furnace slag and ladle slag will be dealt with. This analysis has been carried out in collaboration with the Acciaierie di Sicilia S.p.A. that currently produce eco-sustainable bars, through the electrofusion of ferrous scrap. The objective of this paper is to identify possible alternatives for reusing the furnace slags, for the ladle slags and for the flakes. This would lead to economic advantages deriving from the conversion of landfill costs to revenues obtained from the sale of waste and to increase of the environmental commitment of the steel industry towards the green economy.

Keywords: Circular economy, electric furnace, flake, slag, steel

1. Introduction

Until the 1970s, the extent of the damage generated by waste released into the environment by industries was ignored. Industries adopted an unsustainable model of linear economy and environmental waste pollution into the environment was the main cause of biosphere destruction. Subsequently, the research conducted by the European Commission contributed to the diffusion of a new waste management model, which allowed for the

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extension of the useful life of the products, as well as the reduction of industrial waste released in the ecosystem. This model, called "the circular economy", came from social awareness that the Earth's resources are limited, as well as the space where waste can be placed is limited. The circular economy aims to increase the efficient use of resources, with particular attention to urban and industrial waste, to achieve a better balance between economy, environment and society (Ghisellini et al., 2016). This represents the most recent attempt to conceptualize the integration of economic activity and environmental wellbeing in a sustainable way. It is based on the concept according to which waste from a production cycle is reused as secondary raw materials in a subsequent production cycle (Murray et al., 2017). The use of the second raw material is also convenient since it allows to reduce costs from extracting raw materials from the Earth.

In the collective imagination, the iron and steel industry are one of the most responsible for the quantity of waste introduced into the environment and for the quantity of fumes released into the atmosphere. Contrary to this, more and more steel mills have shown interest in the issue of eco-sustainability in recent years. More in-depth, the management of slags and flakes from steel industry becomes increasingly relevant and, simultaneously with the development of the circular economy model, these two elements have lost the negative meaning of waste, gaining the meaning of resource for a new production cycle. In fact, transforming them into another form to be reused is not only essential for the protection of the environment, but it is also a way to obtain new resources at low cost (Das et al., 2007).

The most important producer of steel in the world is China, which alone generates about 50% of the steel on the market. This gives to China a significant responsibility for waste and pollution created during production processes. Currently, China reuses only 22% of the waste it produces, very far from France, Japan, the USA, and Germany that reuse almost 100% of the waste produced. This has involved an increase in research on the methods of re-using steel waste in recent years (Yi et al., 2012). Companies of steel industry who decide to invest in the green economy, reusing their waste or giving it to other industries, have first of all economic objectives: costs of the landfill are translated both in reduction of expenditure for the purchase of raw materials, through the reintroduction of waste upstream of its production cycle, as well as in revenues resulting from the sale of wastes to other parties. These companies also have environmental and marketing objectives, as a company which obtains certifications is a company that always tends to reduce its environmental impact to a minimum, as well as improving their reputation in the eyes of suppliers, customers, investors and institutions. Furthermore, environmental certifications must not be underestimated because, through these tools, a company defines its goals to continuously improve its operational efficiency, to attract new market opportunities and, in this way, it is subject to continuous monitoring of compliance with the rules.

The objectives of this research are to propose valid re-use alternatives for electrical furnace slags, for ladle furnace slags and for steel flakes. The paper must take into account the methods of reuse already implemented by Acciaierie di Sicilia S.p.A. to achieve this objective, proposing to the company solutions that have been tested in recent years in other parts of the world.

2. Material and methods

Slags and flakes are solid wastes from steel production. Slags are obtained during the melting of wrecks in the furnace and they are mainly composed of SiO_2, CaO, Fe_2O_3, FeO, Al_2O_3, MgO, MnO, P_2O_5. Steel slags are generally considered non-hazardous wastes due to the low leavability of their residues. The waste can be classified into electric furnace slags

and ladle furnace slags (Baciocchi et al., 2009). Steel flakes, on the other hand, come from the steel rolling (which can be hot or cold) and they are composed of 95% iron oxides.

2.1. Electric furnace slags

The analysis of the chemical and physical characteristics of steel slags is strictly related to the methods of reuse of the same (Tables 1, 2).

Table 1. Chemical composition of steel slags

Oxides/%	***CaO***	***SiO_2***	***Al_2O_3***	***Fe_2O_3***	***FeO***	***MgO***	***MnO***	***P_2O_5***
Electrical Furnace Slags	30-50	11-20	10-18	5-6	8-22	8-13	5-10	2-5

Table 2. Characteristics and applications of steel slags

Characteristics	***Applications***
Hard, wear-resistant, adhesive, rough	Aggregates for road and hydraulic construction
Porous, alkaline	Waste water treatment
FeOx, Fe components	Iron reclamation
Cementitious components (C_3S, C_2S and C_4AF)	Cement and concrete production
Fertilizer Components (CaO, SiO_2, MgO, FeO)	Fertilizer and soil improvement

2.2. Utilization for road and hydraulic construction

The high density, the high level of resistance and abrasion, as well as the rough structure qualify steel slags among the best construction materials for hydraulic engineering purposes. Since 1993 the Nippon Slag Association has been involved in the research on application technology for the use of electric furnace slags as material for port construction. In 2008, it published the "Guide to the Use of Steelmaking Slag in Port and Harbor Construction "(Yi et al., 2012). Electric furnace slags also have a high resistance to friction and abrasion, and this allows their use not only in the surface layers of the floors, but also in the surface layers of the asphalt. In Japan and Europe, almost 60% of slags is used in road engineering.

Asphalt composed by slags was placed on the highway between Wuhan and Huangshi and, after two years of monitoring, the results and performance of the asphalt were excellent. Furthermore, in recent years research in China has led to the conclusion that electric furnace slags flooring has even better characteristics than traditional asphalt (Yi H. et al., 2012).

2.3. Utilization for materials of waste water treatment

The application of steel wastes in the waste water treatment has received intense attention in recent years. In fact, some experiments have shown how steel slags can set in motion absorption processes for some water polluting substances. For example, Chamteut et al. (2012) demonstrated that slags could be used as a low-cost adsorbent for arsenic in aqueous system, showing 95–100% removal efficiency. Shi et al. (2011), on the other hand, has studied the absorption of mercury into sea water by slags. Furthermore, the combined use of slags and H_2O_2 can decompose organic pollutants, due to the ferrous ion produced by the FeO released thanks to the reaction with hydrogen peroxide (Yi et al., 2012).

2.4. Utilization for production of cement and concrete

If ground, electric furnace slags are transformed into fine powder, they can be used as an additive for cement and concrete. Feng et al., (2011) has mixed the steel slag powders with fly ash and cement clinker, forming a composite cement, and Feng discovered that the porosity of the cement can be reduced thanks to the use of slag powders, that increase its consistency. The pulverization of steel slag is convenient both for low energy consumption and for the low grinding index. It has been observed that concrete made of steel slag powders has a compressive strength from 1.1 to 1.3 times more than common concrete. Ducman et al., (2011) produced refractory concrete during an experiment, using electric furnace slag as an additive. It has been noted that if the waste reaches a temperature of 1000 ° C, the final product consisting of the refractory concrete has mechanical properties comparable to those of the concrete produced through bauxite (Yi et al., 2012).

2.5. Application in agriculture

Steel slags, containing components such as CaO, SiO_2, MgO, FeO, MnO e P_2O_5, can be used for a wide range of agricultural purposes: above all, the alkaline property is noteable, useful for correcting the acidity of soils. In developed countries such as Germany, USA, France and Japan, steel slag is used for the production of siliceous fertilizer and micronutrient fertilizer (Yi et al., 2012).

2.6. Ladle furnace slags

Natural spelling - clayey soil have often to be stabilized by mixing them with materials as cement and lime, so that they acquire the necessary properties for public works. Ladle furnace slags can be used for this purpose and it was studied that the behaviour of the soil composed by slags is similar to the behaviour of the soil composed by lime or cement (Manso et al., 2013).

2.7. Steel flakes

Until a few years ago, steel flakes were considered unreusable wastes. After having studied their use in the constitution of iron alloys and in the production of cement, it has been discovered that the lamination flakes, composed of about 70% of iron oxides, can be reused also in the production of pellets (Table 3). In the experiment, flakes were reduced to a size of about 40 μm, then they were mixed in magnetite concentrations. Subsequently, bentonite (with binder function) was added, 0.8% in each mixture.

Table 3. The chemical composition of steel flakes in weight per cent

Component	***Total iron***	***Elemental iron***	***Fe^{+2}***	***Fe^{+3}***	***Cu***	***Mn***	***Si***
Content, wt%	71.06	1.15	39.06	30.85	0.35	0.67	0.22

Three batches were prepared, one of which without lamination flakes, so that the pellet consisting essentially of magnetite concentrate could be evaluated. The operation was carried out in a 40 cm-diameter multipex pelletizing disc by adding water to the mixture.

The produced pellet was then dried a first time at 110 ° C for ten hours; then it was dried again at 1250 ° C for one hour. Finally, the pellet was subjected to a crushing and fall test from about 50 cm in height, where the number of falls necessary for the fracture of the product was recorded (Şeşen et al., 2016).

3. Case study: Acciaierie di Sicilia S.p.A.

The company "Acciaierie di Sicilia S.p.A." is located in the industrial area of Catania, and it is a member of the "Alfa Acciai" Group. Thanks to its geographical position, the company represents a valid point of reference for the southern Italian market, as well as for exports to the Mediterranean countries. The production cycle begins from wrecks, the fundamental raw materials for the steel mill, which are first separated and classified, then refined in a 70-ton electric oven. Here, electric furnace slags are produced, consisting of complex solutions of oxides, and to a lesser extent of sulphides and phosphates, which are formed in all the processes of treatment of ferrous alloys in the liquid state and which float on the metallic bath. They are sold by the company to third parties and then they are reused both as road surface and for the construction of asphalt. After the melting of wrecks, the continuous casting of the molten steel produces billets with a square section of 130 mm per side and 11 meters of length, intended for hot rolling, occurs through a group of rough and intermediate cages. The rolling phase determines the formation of the flakes, collected, sold and reused as additives in the production of special cements. They are also sold to other steel mills, which reuse them for the furnace feeding, an opportunity that cannot be exploited by Acciaierie di Sicilia SpA, which uses an electric furnace. Ladle furnace slags, on the other hand, are obtained by casting cast iron into a ladle. This type of slag is sent to recovery plants.

The steel mill, in addition to representing an excellence in terms of eco-sustainability for Sicily is by far the most proactive steel industries in Europe. This result was achieved thanks to the large investments made for the construction of a new plant for collecting and removing dust from the melting furnace, in August 2010. It is characterized by a filtering area of 12,000 m^2 and it is able to reach minimum levels of emissions, well below the legal limits. Acciaierie di Sicilia S.p.A. mission consists not only in obtaining a product of the highest quality, but also in environmental sustainability: the two conditions are achieved together through the production of eco-sustainable steel of the B450C S type, highly performing in relation to the anti-seismic behavior of structures.

The company has confirmed its commitment to the green economy for many years, obtaining environmental certifications such as EN ISO 14001: 2015, which allows the company to reduce its CO_2 emissions by 40%, water and energy respectively of 14 % and 20%, as well as allowing a better awareness of waste management (Milazzo et al., 2017). Another important certification obtained by Acciaierie di Sicilia S.p.A. is the Environmental Product Declaration (EPD), which, besides being a useful safeguard for the protection of the consumer, is also a valid support tool for the decisions made by the management, in order to implement actions that can minimize the environmental impact during all phases of the production cycle (Palmieri et al., 2017). Other certifications achieved by the company are ISO 14025, LCA, SUSTSTEEL.

4. Results and discussion

4.1. Electrical furnace slags

The various technologies for the reuse of the furnace slags described in this paper demonstrate how these products were considered as wastes until recently. Indeed, furnace slags are versatile resources, which can be employed in different uses based on the constituent element that must be exploited. Some of these methods of re-use may represent a starting point to work on for future technologies for Acciaierie di Sicilia S.p.A. The use of slags in the production of agricultural fertilizers differs from the other methods: it was launched in China, where the first steel slags fertilizer program was implemented by the joint venture established in 2011 by Taiyuan Steel Group and Harsco Corporation.

Through the joint venture, which will end in 2036, Harsco Corporation will apply its separation technologies to extract some useful metals from the waste produced by Yaiyuan Steel Group: Harsco's separation processes recover over 99.8% of all metals from slags of stainless steel and also give rise to a product rich in calcium silicate that has shown significant benefits for agricultural productivity.

4.2. Ladle furnace slags

After many experiments, it was observed that the mixtures of clayey soils and ladle furnace slags have resulted in improvements to their bearing capacity in relation to the natural ground soil and the results are very similar to those obtained for the stabilization of soils with lime. This method of reuse is related to the production of asphalt and road sub-base already put in place by Acciaierie di Sicilia S.p.A. for the utilization of the electrical furnace slags.

4.3. Steel flakes

The experiment on the re-use of flakes in the production of pellets showed that, following the pellet drop test, the number of falls necessary for the fracture of the product decreased with the increase in the quantity of lamination flakes present in the pellet itself. In particular, the batch of pellets composed of 50% flakes has resisted 5 falls from a height of 50 cm before fracturing. A similar correlation was also noted in the crushing test, where the same batch of pellets resisted up to a force of 9 N, less than the lot consisting of 40% flakes. This is a significant result because, depending on the industrial use that the pellet could obtain, the most efficient results were recorded with pellets containing a percentage of lamination flakes ranging from 40% and 60%.

It is important to specify that the lamination flakes cannot be reused in plants that use the electric oven, due to the absence of the sintering function of the plants themselves. This use is related to the method already adopted by Acciaierie di Sicilia S.p.A. related to the production of ferrous alloys, so this is not a technology unknown to the company. Despite this, the use of flakes in pellet production could represent a future opportunity, although research on this topic is still in its infancy and only a few industries adopt this method of reuse.

5. Conclusions

Among the alternatives studied in this research, those relating to the electric furnace slags are still in an embryonic phase and they need time to be able to be more concretely explored. On the contrary, the most technologically advanced methods of reuse, such as the use of slag for the production of asphalt or steel flakes for the production of iron alloys, are reuse methods already adopted for some time by Acciaierie di Sicilia S.p.A.

It can be said, for this reason, it can be said that the company is among the most proactive in Europe in relation to environmental management problems, as well as it is a leader in the management and research of alternative solutions for the reuse of slags and steel flakes from steel mills.

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