USAGE OF STEEL SLAG AS A CONSTRUCTION MATERIAL AND IN ENVIRONMENTAL APPLICATIONS

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Abstract: Steel slag is a by-product in the production of steel. An increase of its production results in more landfills. It is mostly used as a building material in the construction of roads, where it substitutes natural materials. The use of steel slag in road construction has multiple benefits; both by solving the challenges of waste disposal and preserving environmental resources by moderating the consumption of non-renewable and natural aggregates. Apart from being used as a building material, steel slag is also used in numerous environmental applications, such as soil and water remediation and CO_2 sequestration. However, a multidisciplinary environmental impact study of steel slag, particularly regarding both the aquatic and terrestrial organisms, is lacking. Steel slag contains traces of potentially harmful elements that endanger these living organisms, including heavy metals released into the environment. A high pH value can also significantly influence their leaching properties, thereby affecting the organisms in the water and soil. Given the widespread utility of steel slag, it is recommended to make a thorough risk assessment associated with the various environmental applications of this material.

Keywords: environmental assessment; road construction; steel slag; leaching; environmental remediation

UPORABA ČELIČANSKE ZGURE: GRAĐEVNI MATERIJAL I PRIMJENA U OKOLIŠU

Sažetak: Čeličanska zgura je nusproizvod u proizvodnji čelika, a porastom proizvodnje sve je više odlagališta. Čeličanska zgura koristi se kao građevni materijal u gradnji cesta, gdje zamjenjuje prirodne materijale. Uporaba čeličanske zgure u gradnji cesta ima brojne prednosti, kao što je rješavanje problema zbrinjavanja ovoga otpada i smanjivanja štetnog utjecaja na okoliš zbog smanjene uporabe neobnovljivih prirodnih agregata. Osim kao građevni materijal, čeličanska zgura primjenjuje se u okolišu na različite načine, poput remedijacije tla i vode te sekvestracije CO_2. Međutim, multidisciplinarno istraživanje utjecaja čeličanske zgure na okoliš, osobito na kopnene i vodene organizme, nedostaje. Čeličanska zgura sadrži male količine potencijalno toksičnih tvari za organizme, kao što su teški metali koji mogu dospjeti u okoliš. Visoka pH vrijednost također može imati važan utjecaj na procjeđivanje teških metala pa samim time i na organizme u vodi i tlu. S obzirom na sve češću uporabu čeličanske zgure, bilo bi korisno napraviti procjenu rizika povezanu s različitim primjenama ovoga materijala na okoliš.

Ključne riječi: utjecaj na okoliš; gradnja cesta; čeličanska zgura; ispiranje; remedijacija okoliša

1 INTRODUCTION

In the last few decades, steel slag has been widely utilized in the construction industry, particularly in road construction, as a substitute for natural aggregates. However, the use of steel slag in other environmental applications is gaining new research interest. Steel slag is an industrial by-product in the production of steel and classified as a waste material. Approximately 20 million tons of slag is produced annually in Europe alone [1]. On an average, the production of one ton of steel generates 200 (EAF) to 400 kg (BOF) of by-product, including slag, dust, sludge, and other materials; more than 400 million tons of iron and steel slag is produced annually worldwide. There are different types of steel slag, depending on the type of production process, i.e., type of furnaces used in production, and the cooling process. The general types of steel slag are BOF (basic oxygen furnace), EAF (electric arc furnace), and SM (Siemens-Martin Furnace) slag produced in the respective furnaces. Although steelmaking slag is typically air-cooled, depending on the cooling conditions, the slag is divided into: a) crystalline slag, cooled in ambient conditions; b) granulated slag cooled in water and subjected to air quenching; and c) expanded or foamed slag, cooled in controlled quantities of water, air or steam.

The main chemical compounds of steel slag, as shown in table 1, are calcium, aluminum, magnesium, and iron oxides, and their relative proportions accommodate the process of making steel and cooling rate of the slag [2]. The air-cooled steel slag, which is highly angular in shape, possesses a rough surface texture, high bulk specific gravity, and moderate water absorption, is crushed before its potential application in the building industry.

Table 1 Chemical composition of different type of slag (oxide composition %)

References	Type of slag	Oxide composition %				
		CaO	SiO_2	Al_2O_3	MgO	Fe_2O_3
Das *et al.* [3]	BOF	47.9	12.2	1.2	0.8	-
Poh *et al.* [4]		52.5	10.8	1.3	5.04	10.01
Juckes *et al.* [5]		36.4-45.8	10.7-15.2	1-3.4	4.1-7.8	-
Mo *et al.* [6]		42.42	11.04	1.61	7.19	23.73
Mahoutian *et al.* [7]		39.08	12.47	6.87	10.57	19.48
Shi *et al.* [8]		30-55	8-20	1-6	5-15	-
Barra *et al.* [9]	EAF	29.5	16.1	7.6	5.0	32.56
Luxan *et al.* [10]		24.4	25.4	12.2	2.9	-
Mahoutian *et al.* [7]		35.23	9.41	10.78	9.77	24.22
Manso *et al.* [11]		23.9	15.3	7.4	5.1	-
Shi *et al.* [8]		35-60	9-20	2-9	5-15	-
Tossavainen *et al.* [12]		38.8	14.1	6.7	3.9	20.3
Tsakiridis *et al.* [13]		35.7	17.5	6.3	6.5	26.4
Johnson *et al.* [14]	Steel slag	51.05	25.80	2.31	9.32	0.72
Mo *et al.* [6]		42.42	11.04	1.61	7.29	23.73
Moon and Choi [15]		54.30	17.70	6.40	9.20	3.00
Xuequan *et al.* [16]		45-60	10-15	1-5	3-13	3-9

2 STEEL SLAG AS A CONSTRUCTION MATERIAL

Since the 1880s, when steel slag was first used as a soil enhancer [17], the possibility of its application in various domains has been explored. An extensive literature review on the applications of steel slag in civil engineering is presented in [2], and several studies covering its applications in other branches of civil engineering have been proactively undertaken. Particularly, its use in clinker production is emphasized, as an aggregate in structural concrete and mortar, whose applications are well-known and documented. Recent research also address the advantages of using steel slag as a partial replacement to coarse aggregate in concrete for effective gamma shielding [18].

This study investigates the application of steel slag in road construction for two primary reasons: first, road building, as compared to other sub-disciplines of civil engineering, is the largest consumer of natural resources,

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where steel slag can maximize their preservation; and second, sustainable recycling, that uncovers new material substitutes and their impact on the environment, is essential for road construction materials as pavements and embankment structures are in direct contact with the surrounding soil and potential pollution can infiltrate the groundwater [19].

Steel slag in road construction has multiple benefits, such as tackling the disposal of waste and reducing environmental impact by acting as a reducing substitute for the non-renewable and natural aggregates [20]. This is effectively achieved by applying slag in the unbound base layer of the pavement structure as it entails the maximum thickness (average thickness of the unbound base layer is 20-45 cm and the asphalt wearing layer is 2-8 cm, for example). Moreover, the slag contained in the unbound base layers achieves higher bearing capacity immediately after compaction and can withstand heavy machinery movement during construction [21]. The interconnectivity between slag grains facilitates optimal load transfer that is beneficial for building roads on weaker soils.

Slag can also be used in the stabilized pavement layers. A small amount of binder, which cannot act independently, is combined with different types of metallurgical slag (including EAF slag), which enables slag activation [22]. Adding the binder significantly accelerates strength development, which is most pronounced in the first year of material aging. Laboratory tests affirm satisfactory strength characteristics of a mixture of slag, naturally crushed stone, and low grade cement (class 42.5 N) [23] as well as that of gravel (as aggregate) and a higher rate but lower strength cement (CEM II B / M (PS), class 32.5 R) [24].

Slag usage in the asphalt layers is limited in the first year of application, owing to the instability of the slag volume, lack of careful materials selection, and incongruous construction methods that may induce cracks and surface protrusions [25-27]. However, appropriate weathering along with the use of finer grain size fractions and coating the steel slag aggregate as a bituminous film can help to curb its expansion and invoke desirable properties for the application in asphalt layers [25, 28]. Beside volume instability, the presence of free CaO increases not only the resistance of the bituminous binder to stripping but also the adhesion between the aggregate and binder, which contributes to greater durability of the wearing courses [27, 29]. A major disadvantage of steel slag, as utilized in the construction industry, is the likelihood of volume changes (expansion), considering that substantial proportions of free calcium and magnesium oxides (CaO and MgO) [30, 25] hydrate under the influence of moisture. Calcium hydrates rapidly cause large volume changes in the first few weeks, while magnesium oxide hydrates contribute gradually to the long-term expansion, lasting up to several years [25]. Exposing the slag to atmospheric conditions for longer durations, called weathering, can effectively control the volume instability. However, newer and faster methods have been discovered, such as aging by steam, which entails covering the slag in tarpaulin/sheet followed by injecting it with steam for a period of 48 hours, revelation, and, lastly, natural cooling [26]. Moreover, preventing the formation of CaO and MgO during the steel making process by adding silica sand to the liquid slag and, subsequently, blowing oxygen can help to inhibit expansion [26].

3   STEEL SLAG IN ENVIRONMENTAL APPLICATIONS

Apart from the construction field, unearthing the utilities of steel slag in other environmental applications has also generated significant research interest. Figure 1 illustrates the most common environmental applications of steel slag, including remediation of soil, sediment, wastewater, groundwater, and storm water; and as a soil modifier in agriculture [31]. Furthermore, it facilitates the process of mineral carbon sequestration by storing and reducing CO_2 [32]. Mineral carbonation or mineral CO_2 sequestration involves CO_2 reacting with minerals to form geologically stable carbonates, and using steel slag as feedstock is lucrative, given its high calcium oxide content and alkalinity, which enhances CO_2 mineralization during the carbonation process.

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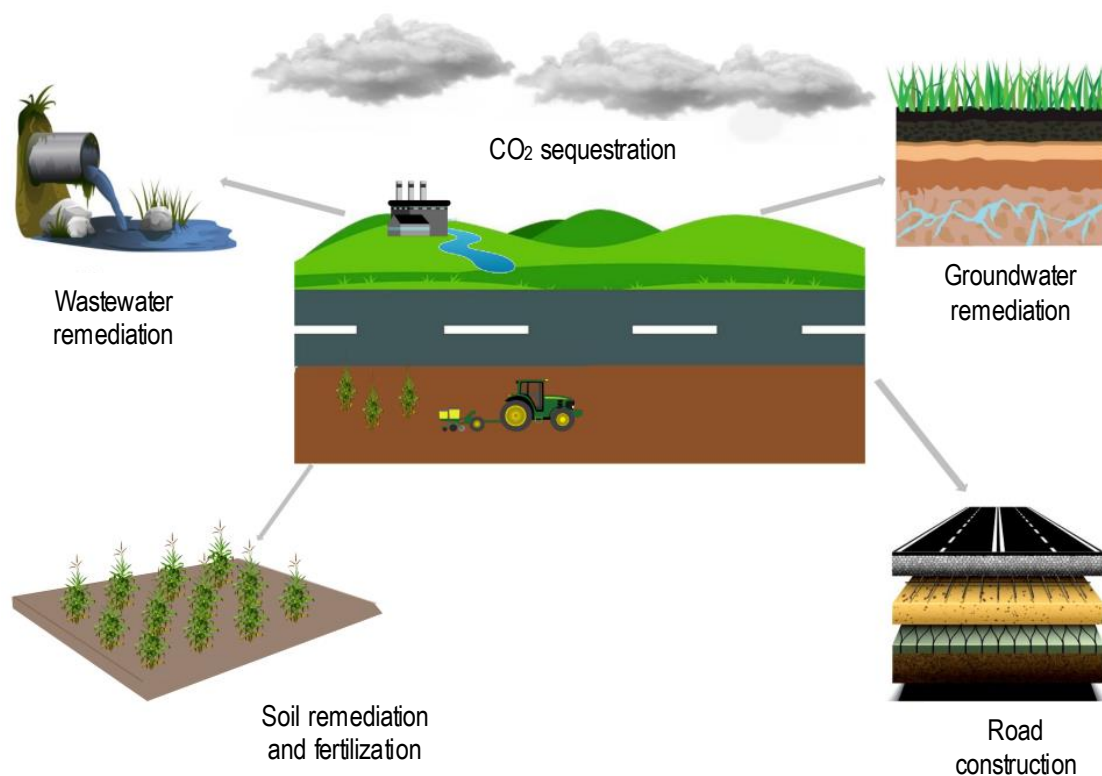
Figure 1 Usage of steel slag in environmental applications

3.1 Soil remediation and fertilization

Polluted and unpolluted soils contain a variety of natural compounds. Soil pollution causes a deterioration or loss of one or more soil functions. The process of purifying and revitalizing the soil is known as soil remediation. Soil pollution by heavy metals is particularly concerning owing to its numerous sources, toxicity, non-biodegradability, and accumulative behavior [33]. Remediating such soils is necessary to ensure food security, restore soil nutrients, and increase soil production by mitigating the associated risks [34]. Various industrial by- or co-products, including steel slag, red mud, and fly ash have been proposed as soil amendments [35]. Regulating the solid-solution equilibrium and pH of the soil is a predominant factor in controlling its metal solubility and bioavailability [36]. These amendments are alkaline and contain a solid phase that enables immobility and adsorption of metals in soil. Steel slag is proposed as a feasible amendment, owing to its physical and chemical properties and the fact that it has been employed, previously, as an amendment and in silicon fertilizers to alleviate the mobility and bioavailability of heavy metals in soils. Steel slag significantly increases the soil pH and reduces the concentration of Pb, Cd, Cu, and Zn in contaminated soils [35]. The results from a study using steel slag as an amendment and in the silicon fertilizer indicate that it helped to increase the soil pH and plant-available silicon concentration, and decrease the bioavailability of metals [37]. Additionally, the co-application of ammonium humate and stainless-steel slag decreased the total and available soil cadmium concentrations significantly [38]. The removal of total and available cadmium by the stainless-steel slag may be attributed to the increased pH (13.96), porosity (14.50%), and surface area (2.31 m^2g^{-1}) essential for satisfactory adsorption. Steel slag is also used to stabilize metals, such as As, Pb, and Cu [39].

Researchers have evaluated the benefits of supplementing steel slag as a fertilizer and soil modifier in order to sustain plant growth [37, 40, 41], where it has catalyzed the rice yield in China by not only increasing the Si-content in the soil, as required to nurture the plant, but also as a fertilizer to modify its acidity for paddy culture [37]. According to Gu *et al.* [42], steel slag can greatly immobilize Cd in the form of silicates, and stop their uptake in plants. Results from another experiment elucidate the usage of steel slag (3 and 6 gkg^{-1}) in increased soil pH levels from 4.0 to 5.0–6.4, 60% decrease in phytoavailability of heavy metals, and suppressed metal uptake by rice. A study by He *et al.* [43] demonstrated that adding steel slag as an amendment to the soil effectively and consistently increased brown rice production and ensured grain Cd levels safe for consumption.

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3.2 Water remediation

Water pollution is a major global environmental concern. Remediation of contaminated ground and underground water is becoming a mounted challenge worldwide. Water remediation is the process to treat polluted water by removing the pollutants or converting them into harmless products. It is crucial that wastewater is treated properly before being discharged into the environment. Steel slag is a promising adsorbent for metal and phosphate removal [31, 44-46]. Previous studies have reported removal rates of 62–79% and 71–82% for the total phosphorous and dissolved phosphorous from effluents, respectively. Additionally, steel slag has shown potential in reducing $Cr(VI)$ from contaminated groundwater via a redox process, where it is used as a reactive permeable barrier [44, 47]. The data presented in Name and Sheridan [48] substantiates the use of BOF slag as a remediation agent to increase soil pH and reduce the soluble iron and sulphate content. Furthermore, WS-EAF steel slag facilitated the removal of high percentages of Cd and Mn ions from aqueous solutions and wastewater, and also highlighted great potential for removal of competitive heavy metal ions in industrial applications [49].

3.3 CO_2 sequestration

Sequestration of CO_2 is the most straightforward way to combat the excessive greenhouse effect [50]. Capturing and storing CO_2 is considered as an efficient and easily adaptable strategy for CO_2 mitigation. Owing to their similarities with natural minerals used in the geological CO_2 sequestration process, slags are a sustainable alternative for industrial-scale carbon capture and storage. Steel slag as an industrial waste is a viable form of feedstock for mineral CO_2 sequestration because it is well-stocked in alkaline oxides, such as CaO and MgO, and has an alkaline pH and low chemical stability. Mineral carbonation involves the dissolution of metal oxides, thereby releasing cations in the solution. These cations then react with the CO_2 forming thermodynamically stable carbonates and, consequently, dispense energy. Sarperi *et al.* [51] discerned the removal capacity per kilogram of BOF slag under ambiental conditions to be 63 g of CO_2. The slag exhibited better performance in terms of carbonation due to its physical characteristics, such as relatively high surface area and pH value. The carbonation reaction occurred in two steps: the steel slag particles facilitated calcium leaching into the solution, followed by calcite precipitation on the surface of particles [52]. Kasina *et al.* [53] reported an increase in the carbonate content in steel slag from 0.8 to 1.4 wt%, and BOF slag from 0.6 to 2.6 wt%. The degree of carbonation is attributed to the mineral composition and their varying solubility. Carbon dioxide can be captured using, both, wet (solution-based) and dry (air) methods. According to Yu and Wang [54] capturing carbon dioxide from air depends on the temperature, CO_2 concentrations, and atmospheric pressure. Their results indicate that the carbonation reaction of steel slag is controlled not only by the reaction kinetics but also the diffusion of the reactive CO_2. A direct CO_2 reduction annually from flue gas was estimated at 0.137 Gt CO_2 when iron and steel slags were applied for CO_2 mineralization [55].

4   CONSIDERATIONS FOR ENVIRONMENTAL USAGE

Before steel slag can be utilized as an aggregate in road construction and environmental applications, such as soil and water remediation, CO_2 sequestration, and soil fertilization, a complete environmental risk assessment is warranted. Although steel slag is not considered hazardous, it is important to investigate the environmental impact, such as changes in the chemical content and properties of the slag in environmental conditions due to heavy metal content, particularly leachable quantities, changes in pH value, and effect on living organisms [54].

4.1. Heavy metal content

Certain types of steel slags contain traces of potentially mobile and toxic elements, such as Cr, Ni, Mn, V, and Mo. Additionally, As, Cd, Co, Pb, Sb, and Zn can also be found [56, 57]. It is essential to predict the long-term behavior of steel slag by determining the rate and mechanisms of the metal release. The toxicity and mobility of these harmful elements depends on factors, such as oxidation state, molecular geometry, and environmental conditions [58]. Chromium is a redox active metal that persists as either $Cr(III)$ or $Cr(VI)$ in the environment. Unlike $Cr(III)$, which is an essential nutrient for plants and has low toxicity at higher content levels, $Cr(VI)$ is toxic for plants. Soils with high content percentages of oxidized manganese and other electron receptors promote the oxidation of Cr^{3+} to CrO_4^{2-}.

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Moreover, the latter oxidation state occurs among leachates in the presence of oxygenated water (with pH levels above 5), given its stability under these conditions. Vanadium exists in oxidation states ranging from 0 to +5, with the most common valence states being +3, +4, and +5. The toxicity of vanadium increase usually as a valance increases proportionally with the valence state. Therefore, an accurate estimation of these oxidation states is vital. Chromium is released less than 0.02% of the total content, while V is released between 0.4 and 0.5%, even during short leaching periods [58]. A study on the leaching process of both these toxic trace elements from the slag when exposed to air currents (dry) and carbonated water (wet) indicated that the treated slag showed leaching levels of below 1% for both elements [59]. It is relevant to known the chemical composition of these leachates and their behavior as the total heavy metal content is not entirely representative of the total released concentration in the environment. The concentration of heavy metals in a leachate depends on the way an element is incorporated into the aggregate matrix [60]. Furthermore, the chemical composition of the leachate can only be used to predict total heavy metal content, as the individual proportions of heavy metal content is not proportional to their total content. However, the individual quantity of these potentially environmentally toxic elements is important in determining the application rate of slag in the environmental applications.

4.2. Leaching

Leaching properties of a material are directly related to the risk of the material releasing harmful substances into the environment. Therefore, a risk assessment supported by the material characterization with leaching and ecotoxicological testing is necessary. One of the most significant environmental impacts of administering and reusing steel slags is the leaching effect, caused by the soluble slag matrix in contact with the soil that is exposed to rainwater or in permanent contact with the surface and seawater. Leaching tests are conducted to estimate the release potential of constituents from the associated waste materials. Leaching processes comprise contact between a liquid and solid material, where the partial dissolution of certain components occurs [57]. Several factors can influence the process viz., physical factors, including particle size, temperature, porosity, permeability, hydrogeological environment; and chemical factors, including pH, redox potential, kinetics, adsorption process, etc. The process also comprises heterogeneous reactions, which may or may not be reversible, and quick or slow. Additionally, after post the metal recovery process, 25% of slag is rendered as a fine-grained powder, which is unusable without treatment, given the elevated leaching of chromium and molybdenum [61].

4.3 pH value

pH is a major parameter controlling leaching in many elements. Steel-industry slags are alkaline and produce water leachates with a pH value between 9-11 [62]. A high pH value can adversely affect the environment and living organisms. According to Piatak *et al.* [63], alkaline leachates result from the dissolution of Ca silicates, oxides, and carbonates, and therefore, an alkaline pH can be harmful for not only the environment but also aquatic life. It increases chemical oxygen demand, sulphate content, and salinity. Elevated pH levels reduce mobility (leachability) of metals in the slag in or near surface water and groundwater bodies that have limited dilution volume, thereby emerging as an impediment in its application [62]. It is expected that the alkaline leachate does not react with huge water bodies or acidic soils, as it gets neutralized under these conditions.

4.4 Impact on living organisms

Steel slag is used in a wide range of environmental applications as well as road construction. However, there is a limited number of multidisciplinary studies on how it affects living organisms, positively or otherwise. The heavy metal content in steel slag is non-biodegradable and tends to accumulate in the food chain, causing various disorders among living organisms. Numerous studies have examined the impact of slags on water organisms [64-66]. Ringelband [64] claims that the vanadium found in slag stones effects the population growth of the brackish water hydroid *Cordylophora caspia* at various salinities. Takahashi and Yokoyama [65] investigated the adverse effects of EAF steel slag on *Chlorella* algae. An analysis of the algal cells treated with eluate revealed no lethality (cytotoxicity) or growth inhibition; instead, it enhanced algal growth. The apparent cytotoxicity in microalgae (*Chlorella sp.*), cladocerans (*Ceriodaphnia dubia*), and bacteria (*Vibrio fischeri*) was attributed to the elemental composition of the slag [66]. Slag leachates with the highest concentrations of dissolved elements were the most

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toxic (10% effective concentration [EC10] 1%), whereas those with the lowest concentrations were the least toxic (EC10 63-85%) [66]. These leachates were not tested at their natural pH values, which was higher than acceptable for algal growth, cladoceran survival, and Microtox testing. Invertebrates, such as earthworms, possess limited movement and can spend their entire lives within the area of slag application, so long as the nutrient and pH conditions permit. The extracts of steel slag did not demonstrate any significant changes in the activities of the molecular biomarker, AChE, in the earthworm *Eisenia fetida* [60]. In humans, a study investigating the potential health adversities associated with the environmental applications of steel-industry slag revealed no significant hazards [63]. Nevertheless, the advantages and disadvantages of employing slags in the environment is reliant on the application rate, which needs to be predetermined for each type of slag as their compositions vary (Table 1), particularly in trace elements. Similarly, in another experiment, red mud (an alkaline bauxite by-product) was used as a soil amendment. The inherent differences in the composition of red muds from different sites affected the reproduction of earthworms and, accordingly, required different application rates to protect the soil biota [67].

5   CONCLUSION

The results from various environmental applications of steel slag appear to be promising and result in a significant reduction of steel slag deposition as more than a waste material. However, a thorough ecological risk assessment should be recommended supported by the characterization of slags and their leachates, prior to the environmental application. There is a lack of data and multidisciplinary approaches concerning how steel slag impacts living organisms and the environment. The chemical characterization and soil pore-water measurements should not be used as sole determinants, given that mixtures of metals, even in small quantities, can inevitably harm living organisms. However, research on the usage of steel slag in construction and environmental applications is encouraged, as it is unlikely that the steel production will stop.

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