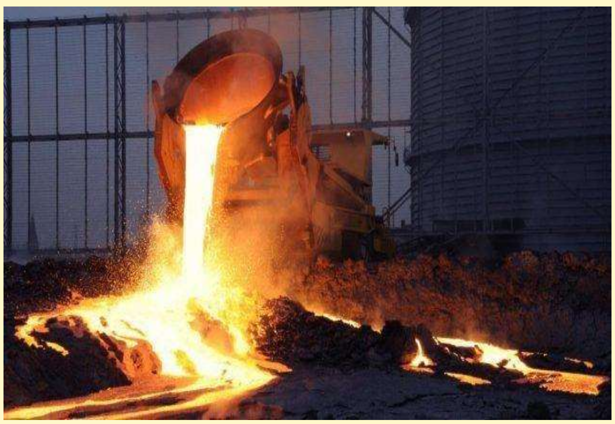
Ministry of Steel
Government of India

GUIDELINES FOR PROCESSING AND UTILIZATION OF STEEL SLAG AS PROCESSED STEEL SLAG AGGREGATES IN ROAD CONSTRUCTION



PREPARED BY

CSIR-CENTRAL ROAD RESEARCH INSTITUTE
NEW-DELHI, 110025

GUIDELINES FOR PROCESSING AND UTILIZATION OF STEEL SLAG AS PROCESSED STEEL SLAG AGGREGATES IN ROAD CONSTRUCTION

Published by:

MINISTRY OF STEEL GOVT. OF INDIA

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CSIR - CENTRAL ROAD RESEARCH INSTITUTE

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Price: Rs. 500/-

Dr. V.K. Saraswat
MEMBER, NITI AAYOG
GOVT. OF INDIA

सत्यमेव जयते

FORWARD

I am delighted to note that the CSIR-Central Road Research Institute and Ministry of Steel has developed a detailed ***Guidelines for Processing and Utilization of Steel Slag as Processed Steel Slag Aggregates in Road Construction*** as an outcome of a major R&D project undertaken by CSIR-CRRI to facilitate large scale utilization of steel slag in road works. This translational research project has facilitated large scale techno-economic conversion of waste steel slag as processed steel slag aggregates for Steel Slag Road construction.

Niti Aayog closely monitored this R&D project and its outcome since its inception. I have visited all the three steel slag road sections built under the study at Surat-Hazira, Dolvi, Maharashtra and Ziro Arunachal Pradesh under CSIR-CRRI technological guidance. I am happy to confirmed that the steel slag roads offer a viable solution for waste management while also demonstrating enhanced durability, reduced maintenance costs and improved resistance to wear and tear compared to conventional roads. These guidelines have been meticulously developed to provide a comprehensive framework for the effective use of steel slag, a by-product of the steel manufacturing process, in the construction and maintenance of roadways. I am confident that these guidelines will optimize natural resource utilization in road construction and maintenance work by providing a cost-effective alternate to natural aggregates besides providing a viable solution to steel industries for utilization of steel slag as byproduct for road construction and maintenance works.

The "Guidelines for Processing and Utilization of Steel Slag as Processed Steel Slag in Road Construction" represent a significant step forward in our commitment to sustainable and innovative infrastructure development. I urge all stakeholders to integrate these guidelines into their planning and operational processes. Training sessions and workshops will be organized to facilitate a smooth transition and ensure comprehensive understanding and adherence to these standards

Date: 25.06.2024

(Dr. V.K.Saraswat)

Nagendra Nath Sinha, IAS
Secretary
Government of India
Ministry Of Steel,
New Delhi- 110001

सत्यमेव जयते

FORWARD

Ministry of Steel is funding R&D initiatives by the stakeholders in finding ways and means to utilize steel slag in potential applications like building construction, road making, soil conditioning etc. However, there is lack of adequate guidelines in utilization of steel slag in the various potential uses which pose a challenge to its utilization.

Under this background, Ministry of Steel had funded a R&D project viz. "Development of Design Guidelines and Specifications for utilization of steel slag in road construction" by CSIR-CRRI in association with the steel industry. As the outcome of the R&D project, CSIR-CRRI in consultation with the steel industry, has formulated the guidelines on processing & utilization of steel slag in road construction.

The aforementioned guidelines have been shared with the stakeholders from the roadmaking sector viz. MoRTH, Ministry of Rural Development, IRC, NHAI, NHIDCL & BRO for consideration in adopting these guidelines in roadmaking activities to promote & enable utilization of processed steel slag in road construction. I am happy to note that IRC is considering updating the existing IRC guidelines (IRC:121-2018) for use of Iron, Steel & Copper Slag in construction of rural roads.

Ministry of Steel had also requested CSIR-CRRI to organize a seminar to showcase the processes & the guidelines developed for processing of the steel slag and utilization in road making. I am happy to know that CSIR-CRRI is organizing an International Conference to disseminate the knowhow & the guidelines developed for utilization of steel slag as substitute of natural aggregates in road construction and maintenance works.

These guidelines are a significant step towards sustainable development and the efficient utilization of industrial by-products in infrastructure projects in the country. The adoption of these guidelines for construction and maintenance of road network using steel slag, is expected to bring numerous benefits, including cost savings, reduced environmental impact, and improved road performance. These guidelines also align with the Government of India's commitment to promoting sustainable development and circular economy practices under the Govt of India's "Waste to Wealth" initiative.

I wish the seminar to be very fruitful in showcasing the processes & the guidelines developed for use by the roadmaking sector. I hope that the guidelines will be widely adopted by the concerned central & state agencies.

Date: 25th June 2024 **(Nagendra Nath Sinha)**

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Prof. (Dr.) Manoranjan Parida,
Director, CSIR-Central
Road Research Institute
New Delhi - 110025

PREEACE

The CSIR-Central Road Research Institute (CRRI) is pleased to present the "Guidelines for Utilization and Processing of Steel Slag as Steel Slag Aggregates in Road Construction". This document marks a significant milestone in our journey towards promoting sustainable construction practices and efficient resource utilization for construction and maintenance of road infrastructure in the country using industrial by product steel slag.

These guidelines have been meticulously developed by CSIR-CRRI, drawing on extensive research and practical experience. Guidelines provide a comprehensive framework for the processing, utilization, and quality control of steel slag aggregates in road construction projects across the country. Key components of the guidelines include:

1. **Challenges with steel slag**: Guideline outline the various challenges associated with utilization of un-processed steel slag in road construction
2. **Processing Techniques:** Best practices for the processing and treatment of steel slag to enhance its properties and performance.
3. **Material Specifications:** Detailed physical, mechanical and chemical properties of processed steel slag aggregates to ensure its suitability in road construction
4. **Environmental and Safety Considerations**: Measures to minimize environmental impact and ensure compliance with safety standards.
5. **Pavement and Mix Design Parameters**: Guidelines for designing road construction materials that incorporate steel slag aggregates, ensuring optimal performance and durability.
6. **Construction Practices:** Recommended methods for handling, transporting, and placing steel slag aggregates in various types of road projects.

We believe that these guidelines will serve as an invaluable resource for engineers, contractors, policymakers, and all stakeholders involved in the construction and maintenance of road infrastructure. By embracing the utilization of steel slag aggregates, we can pave the way for a more sustainable and resilient road network in India.

Sincerely,

New Delhi
Date: 25th June 2024

(Manoranjan Parida)

Satish Pandey
Principal Scientist & Principal Investigator
CSIR-Central Road Research Institute
New-Delhi-110025

ACKNOWLEDGEMENT

CSIR-CRRI want to place on record its deep gratitude to **Ministry of Steel, Government of India**, for their vision and encouragement in promoting sustainable utilization of steel slag in road construction and sponsoring the research project "Development of Design Guidelines and Specifications for Utilization of Steel Slag in Road Construction" to CSIR-CRRI for the development of these guidelines. Ministry of Steel commitment to advancing the utilization of industrial by-products has been instrumental in driving this project forward.

We also sincerely appreciate the vision and guidance provided by the **Niti Aayog**, Govt. of India, to CSIR-CRRI to explore the possible utilization of steel slag as a sustainable material in road construction. Niti Aayog strategic direction and encouragement have been pivotal in the successful completion of this initiative.

A Special thanks is also due to the steel manufacturing companies particularly to **AMNS India, TATA Steel, JSW Steel and RINL** for co-sponsoring the R&D project to CSIR-CRRI. Their active participation and provision of essential data have been critical in understanding the properties and potential applications of steel slag in road construction. Their active contribution in building the steel slag road sections across the country greatly help the CRRI to develop various data for development of these guidelines. Their technical expertise and openness in sharing information have greatly enriched the content of these guidelines.

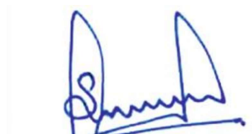
We also profoundly appreciate the contributions of the **Ministry of Road Transport and Highways**, **National Highways Authority of India (NHAI) and Border Road organization** for providing the road sections for field trial of steel slag road. Their practical insights and feedback on field applications have been vital in ensuring that the guidelines are both practical and effective. This study could not be possible without the support of **Indian Road Congress (IRC)** to realize this Research and Development project on the utilization of Steel Slag for road construction. We express our sincere gratitude to Indian Road congress for their support to pursue this R&D study.

Council of Scientific and Industrial Research, CSIR played an important role and extended all possible support to CRRI team for wider dissemination of the steel slag road technology and to showcase it on various national and international platforms. We are deeply grateful to Vice President, CSIR and DG, CSIR for their invaluable guidance and support to the project.

We are also thankful to the various research institutes such as CSIR-NEERI, CSIR-NPL and IUAC, New-Delhi for their technical support in steel slag characterization. Our gratitude also extends to various road contractor and testing agencies who provided all possible support to CSIR-CRRI team to construct the steel slag road sections and its evaluation. Their hands-on knowledge has been indispensable in fine-tuning these guidelines to meet real-world challenges.

At last, but not least, I acknowledge the efforts of the CSIR-CRRI team, whose dedication and hard work have been pivotal in bringing this document to fruition. Their commitment to excellence and sustainability continues to drive our mission of fostering innovative and eco-friendly solutions in the field of road construction.

With deep appreciation and Thanks



New-Delhi
Date: 25th June 2024

(Satish Pandey)

GENESIS OF THE GUIDELINES

The Ministry of Steel, Govt. of India, to address the challenges of safe and sustainable disposal of Steel Making Slag (SMS), sponsored a major R&D project to CSIR-Central Road Research Institute i.e "Development of Design Guidelines and Specification for Utilization of Steel Slag in Road Construction" to explore possible utilization of steel slag in road construction and maintenance. This project was co-sponsored by M/s Tata Steel, AMNS India, JSW Steel and RINL, Visakhapatnam to explore possible utilization of different types of steel slag, i.e. BOF, EAF and CONARC steel slag in road construction as substitutes for natural aggregates. Steel slag, due to several intrinsic challenges, cannot be utilized as such for road construction and requires proper processing. Further, Ministry of Road Transport and Highways (MoRTH) vide office memorandum no. RW/NH-36098/25/2023-S&R (P&B) dated 07th June 2023 requested CSIR-CRRI to provide the design guidelines and specifications for utilization of steel slag in road construction along with processing requirement of slag with details of facility required for processing.

CSIR-CRRI based upon the extensive R&D findings at laboratory and field scale developed the detailed "**Guidelines for Processing and Utilization of Steel Slag as Processed Steel Slag Aggregates in Road Construction**" to carry out techno-economic conversion of steel slag as processed steel slag aggregates and to facilitate its further utilization in road construction and maintenance works. The first draft of this guideline was papered by Shri Satish Pandey, Principal Scientist, CSIR-CRRI and Principal Investigator of the project and further revised by him based upon the observations of Ministry of Steel and various stakeholders. The draft guideline was shared by Ministry of Steel with various steel industries and Indian Steel Association (ISA) on 12th June 2023 for necessary examination and comments. Based upon the comments received from steel industries and ISA, CSIR-CRRI revised the guidelines and submitted the revised draft to Ministry of Steel on 10th July 2023 for further necessary perusal. The revised draft was further circulated by Ministry of Steel to all steel industries and ISA for their comments on 12th July 2023. A detailed deliberation was carried out on revised draft on 27th July 2023 with all stakeholders and steel industries under the chairmanship of Secretary, Ministry of Steel Shri Nagendra Nath Sinha at Udyog Bhawan.

Based upon the observations and comments in the meeting, CSIR-CRRI revised the guidelines and submitted the same to Ministry of Steel on 06th Sept. 2023. Revised draft guidelines were further circulated by MOS to all stake holders comprising Ministry of Road Trasport and Highways (MoRTH), MoEFCC, CPCB, NHAI, IRC and various steel industries on 25th Sept. 2023 for necessary comments and observations. The revised guideline was further deliberated in the meeting of all stakeholders under the chairmanship of Secretary, Steel on 04th Oct. 2023 at Ministry of Steel. Based upon the minutes of the meeting CSIR-CRRI further revised the guidelines and submitted the revised draft to Ministry of Steel for further consideration on 31st Jan. 2024. Revised draft guidelines was once again circulated by Ministry of Steel on 23rd February 2024 to all stakeholders for necessary examination and comments. Based upon the observation guideline are further revised and approved for printing and officially released on 29th June 2024 during International Conference on Steel Slag Road. Name of the organization and industries who made important contribution in the development and reviewing process are as follows:

PREPARED BY : CSIR-CENTRAL ROAD RESEARCH INSTITUTE, NEW -DELHI

REVIEWED BY : TECHNICAL DIVISION OF MINISTRY OF STEEL

INDIAN STEEL ASSOCIATION

TATA STEEL

JSW STEEL

ARCELOR MITTAL NIPPON STEEL INDIA

STEEL AUTHORITY OF INDIA LIMITED

JINDAL STEEL & POWER LIMITED

RASHTRIYA ISPAT NIGAM LIMITED

NATIONAL HIGHWAY AUTHORITY OF INDIA

Printed copy of the guideline and further clarifications for utilization of processed steel slag in road construction can be obtained from following:

Mr. Satish Pandey
Principle Scientist and Principal Investigator
Coordinator Centre for Research on Steel slag
CSIR-Central Road Research Institute
Delhi-Mathura Road New-Delhi
satishpandey.crri@nic.in, satishpandey.crri@gmail.com

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1.0 INTRODUCTION

India is having world's second largest road network in terms of length and further embarked into a large-scale highway expansion and upgradation program to facilitate unhindered freight and passenger movement in the country at economical cost. Govt. of India under "Bharatmala" project and "National Highway Development Program" is vigorously building a solid network of roads, highways, and expressways in the country. For construction and maintenance of this vast road network a huge quantity of natural aggregates is required every year. For construction of a 1 km long six lane road, around 60 to 70 thousand tonne of natural aggregates are required in a green field project. This demand is fulfilled through unsustainable quarrying and mining of rocks, which is causing serious environmental impacts such as loss of forest cover and natural habitats, desertification, topographical changes leading to water, air and land pollutions etc. Besides that, the availability of this perishable mineral resource is limited owing to many highway projects are facing acute scarcity of good quality natural aggregates to construct and maintain road network.

India is world's second largest steel producer with annual steel production of around 125 million tonne in 2022. For every tonne of crude steel production around 150 to 200 kg steel slag is generated as solid waste, which yields, 19 to 20 million tonne of steel slag generation annually in the country through various steel plants. National Steel policy of India envisages crude steel production in the country to the tune of 300 million tonne per annum by 2030, with the expected capacity augmentation in various integrated steel plants. Accordingly, steel slag generation in the country is also expected to reach to 55 to 60 million tonne per annum by the end of 2030. Majority of steel slag after metal recovery is disposed of as solid waste. Disposal of steel slag as solid waste occupied large tracts of lands in and around the steel plants and become the source of land, air and water pollution. Potential utilization of steel slag as "Processed Steel Slag Aggregates for Road Making" can provide a good alternative/substitute of natural aggregates for road construction.

These guidelines for Processing and Utilization of Steel Slag as Processed Steel Slag Aggregates in Road

Construction are the outcome of R&D study entitled "**Development of Design Guidelines and Specification for Utilization of Steel Slag in Road Construction"** carried out by CSIR-Central Road Research Institute, New-Delhi under a sponsored research project of Ministry of Steel, Govt. of India. Guidelines are based on the research findings of CSIR-CRRI, emanated out of various steel slag road sections built across India using **processed steel slag aggregates** of Basic Oxygen Furnace/LD Converter (BF-BOF), Electric Arc Furnace (EAF) and CONverter ARCing (CONARC) Steel Slag of TATA Steel, JSW Steel, AMNS India and RINL ,Visakhapatnam steel plants.

1.1 STEEL SLAG PRODUCTION IN INDIA

Indian steel industry is structured in four broad categories based on route wise steel production viz. Basic Oxygen Furnace/LD Converter (BF-BOF), Electric Arc Furnace (EAF), CONverter ARCing (CONARC) and Induction Furnace (IF) route of steel production. Figure 1.1 shows the footprint of steel industries in India corresponding to BOF and EAF/IF steel production routes.

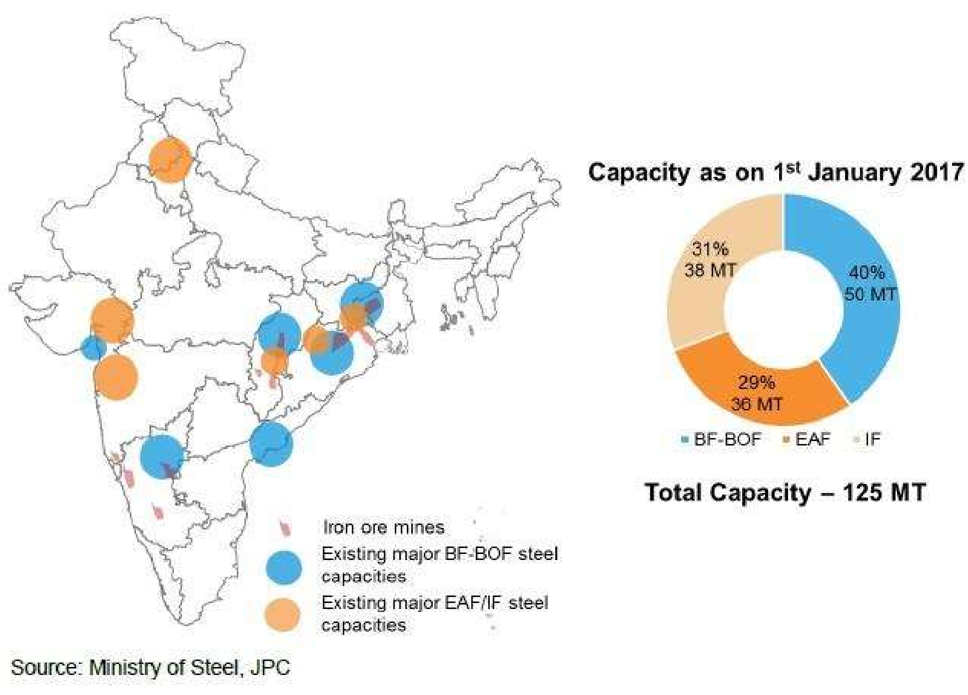


Figure 1.1: Current Steel Footprints in India

Steel slag is generated during the separation of impurities from the molten steel in steel- making furnace for production of low carbon steel. The steel slag is produced as a molten liquid melt, as a complex solution of silicates and oxides that solidifies upon cooling in slag pit. In an integrated steel plant around 2-4 tonnes of waste (including solid, liquid and gas) are generated for every tonne of steel production. Typical process flow of Iron and Steel Production and various common steel products of steel industries is shown in figure 1.2.

Slag output obtained during pig iron and steel production is variable and depends mainly on composition of raw materials and type of furnace. Typically, for iron ore feed containing 60 to 65% iron, blast furnace (BF) slag production ranges from about 300 to 540 kg per tonne of pig or crude iron produced, whereas 150 to 200 kg per tonne of steel slag is generated for per tonne of liquid steel production. Lower grade ores yield much higher slag fractions, sometimes as high as one tonne of slag per tonne of pig iron produced. Steel slag output is approximately 20% by mass of the crude steel output.

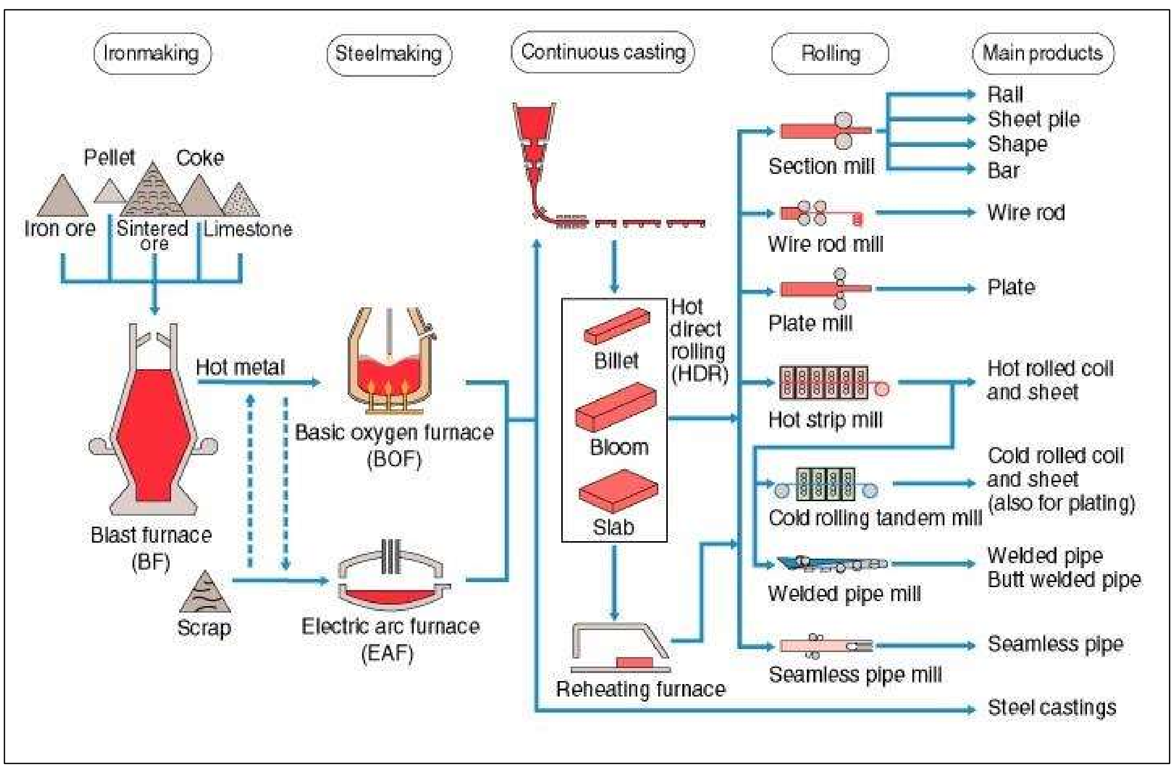


Figure 1.2: Typical process flow of Iron and Steel Production
(Source: An Introduction of iron and steel processing, Kawasaki Steel 21st Century Foundation)

Therefore, steel industries should pay adequate emphasis on minimization of waste generation from the steel plants, recycling and re-use of generated waste, to minimize the adverse impact of unscientific disposals of slag on environment. Among all the solid/liquid wastes generated in steel plant, steel slag has negligible reuse thus management of slag has become a critical component to steel industries. With increasing steel production capacities in steel plants, the mechanism for disposal of large quantities of slag that get generated during steel production could become critical for steel makers. Over the last few years, with better understanding of slags, its functions and improvements in process technologies have led to a significant reduction in the volume of slag generated in steel plants. At the same time, the re-use of iron and steel slag has led to a significant reduction in the environmental impact of these by-products. However, slag generation remains inevitable and emphasis on its utilization remains one of the most serious concerns that need redressal.

2.0 TYPES OF STEEL SLAG

Steel slag is a by-product of steel making operations. The calcined lime used as a fluxing agent and combines with the silicates, aluminum oxides, magnesium oxides, and ferrites to form steel furnace slag, commonly called as steel slag. During primary steel making four types of Steel Slag are largely generated in India:

- Basic Oxygen Furnace Steel Slag or LD Slag (BOF/LD slag)
- Electric Arc Furnace Steel Slag (EAF Slag)
- Converter Arcing Furnace Steel Slag (CONARC slag)
- Induction Furnace Steel Slag (IF Slag)

During secondary steel making process (alloy or special grade steel), ladle furnace slag is generated. Integrated steel plants in India are largely producing BOF/LD, EAF and CONARC steel slag to produce low carbon steel through primary steel manufacturing process using different types of steel furnaces. Induction Furnace Steel Slag is mainly produced in small MSME steel industries during production of various alloy steel and medium to high carbon steel. Induction furnace can use various types of scrap like stainless steel scrap and galvanised steel scrap for steel production which can result into a wide variety of steel slag containing light to heavy metals, harmful to environment. These guidelines for processing of steel slag as road making aggregates are only applicable to steel slag generated during Low Carbon Steel Production in Basic Oxygen Furnace (BOF/LD converter), Electric Arc Furnace and CONARC furnace. Induction Furnace steel slag, Stainless Steel Slag and Ladle Furnace slag are not the part of these guidelines.

2.1 BOF OXYGEN FURNACE STEEL MAKING AND BOF SLAG GENERATION

BOF/LD steel slag is generated during Basic Oxygen steelmaking (BOS or BOF), also known as Linz-Donawitz-Verfahren steelmaking or the oxygen converter process. Basic Oxygen Furnace process is a method of primary steelmaking in which carbon-rich molten pig iron is converted into steel. Blowing oxygen through molten pig iron lowers the carbon content of the hot metal and changes it into low-carbon steel. This process is known as basic due to the type of refractory's i.e. calcium oxide and magnesium oxide, that line the vessel to withstand the high temperature of the molten metal. The majority of steel manufacturing in integrated steel plants in India happens through BOF route, which accounts for approximate 60% carbon steel production in the country. BOF process starts with charging of both molten iron or hot metal with steel scraps in the furnace. Typically, the basic oxygen furnace charge balance consists of approximately 10-20% of steel scrap and 80-90% of molten iron. Fluxes (burnt lime or dolomite) are fed into the BOF vessel to absorb impurities and to form steel slag. During this process a high basicity more than 3 is maintained in the BOF vessel for steelmaking. During "blowing," churning of metal and fluxes in the vessel, forms an emulsion, that facilitates the refining process. After the steel is poured off from the BOF vessel, the slag is poured into the slag pots through the BOF vessel. Molten slag is then transported to slag pit for water and air cooling. Figure 2.1 shows a schematic representation of a basic- oxygen furnace and the main chemical reactions occurring in the furnace.

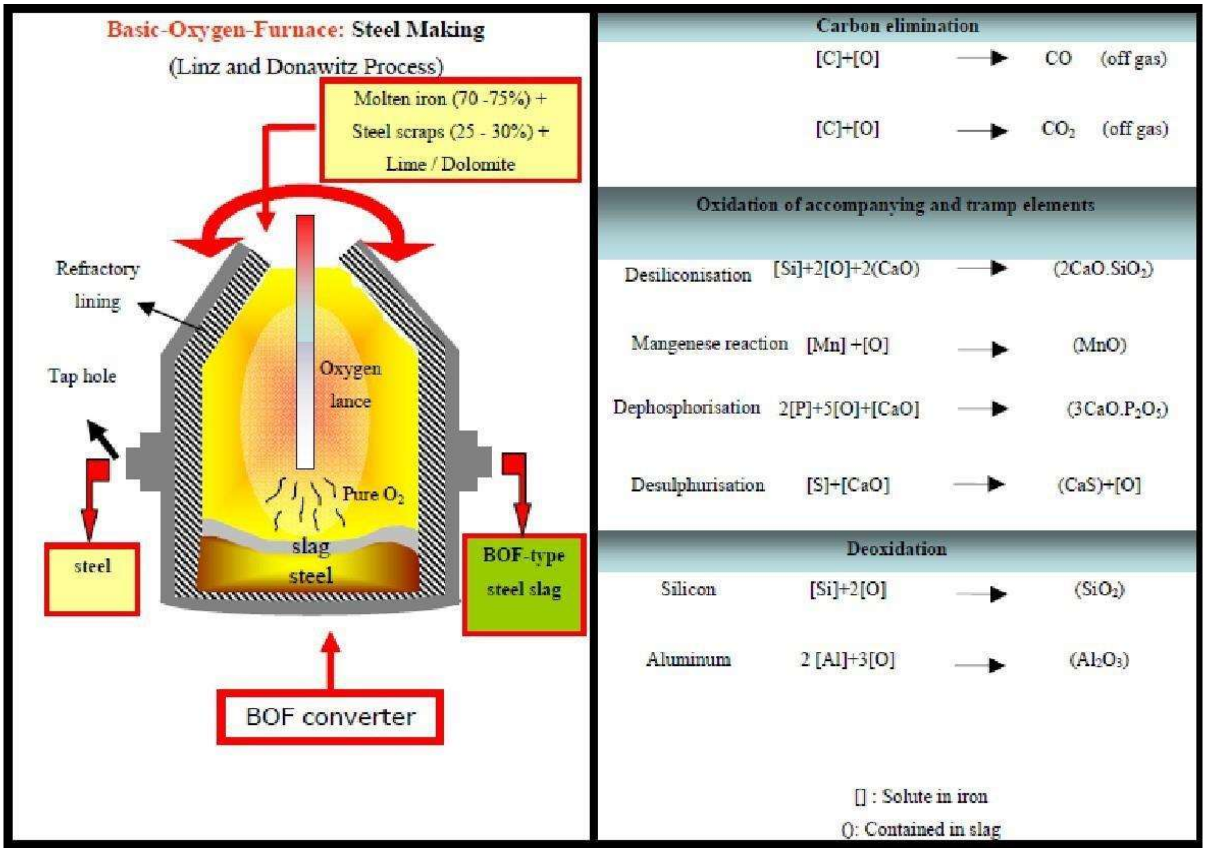


Figure 2.1: Schematic representation of the basic oxygen furnace process and the reactions involved in BOF steelmaking (modified after Schoenberger 2001 and http://www.steel.org)

The chemical reactions occurring during the removal of impurities determines the chemical composition of the basic-oxygen-furnace steel slag. The main chemical constituents of basic oxygen- furnace slag is CaO, FeO and SiO_2. During the conversion of molten iron into steel, a percentage of iron (Fe) in the hot-metal cannot be converted into the steel produced. This oxidized iron goes with slag and found in the chemical composition of the basic oxygen-furnace slag. Besides that the small quantity of Metallic iron also goes with slag in slag pot during de-slagging process in the furnace. This metallic iron content in the slag varies from furnace to furnace depending on the efficiency of the refining and de-slagging process in the furnace. FeO content in basic-oxygen-furnace slag can vary between 10 to 40% while metallic iron content generally varies from 5 to 15 %. SiO_2 content in basic-oxygen furnace slag is much lower as compared to blast-furnace slag as most of the silica impurities in iron ore are already trapped in the blast-furnace slag using fluxing agent.

Large quantities of lime or dolomitic Lime is used as fluxing agent in BOF furnace during refining period of conversion from iron to steel hence the CaO content of BOF slag is typically very high (CaO > 35%). Although, most of the lime (CaO) or periclase (MgO) exists in crystalline bound forms with other constituents in BOF Slag but small quantity of lime (unbound) typically between (0-10%) and magnesia (typically between 0-10%) exist in free form. This free lime (CaO) and magnesia (MgO) hydrate expansively and these hydration reactions attributes volumetric instability to the BOF/LD Steel Slag besides high pH value.

2.2 ELECTRIC ARC FURNACE (EAF) STEEL MAKING AND EAF SLAG GENERATION

Electric Arc furnaces are typically charged with steel scrap. Electric Arc furnaces use high-power electric arc instead of gaseous fuels, to produce heat which melts recycled steel scrap and converts it into high-quality steel. They also convert direct reduced iron (DRI) into liquid steel, reaching the same quality that can be achieved in an integrated steel plant. In the electric arc furnace of steel making through DRI route around 250 to 300 kg. EAF steel slag is generated, while EAF steel slag generation remain limited to the range of 100 to 150 kg slag per ton for every ton of steel production when the steel scarp is used predominantly for steel production. The electric-arc furnace steel making process is independent of the blast-furnace production. Electric-arc furnaces are equipped with graphite electrodes and they look like giant kettles with a spout or an eccentric notch on one side. Figure 2.2 shows a picture of an electric-arc furnace and a shaft for scrap charging. The main feed of electric- arc furnaces is steel scrap and Direct Reduced Iron (DRI). DRI and steel scrap charge in the furnace varies as per requirement and availability.

During the steel production, the basicity in Electric Arc Furnace is kept less than 2, therefore majority of EAF steel slag does not exhibit volumetric instability caused by free lime and magnesia as in the case of BOF steel Slag. CaO, FeO, SiO2 and Al2O3 are the main components of electric-arc-furnace slag. Other minor components include the remaining oxidized impurities in the form of MgO, MnO, SO3 etc. Fig. 2.2 shows the schematic representation of the Electric-Arc- Furnace steel making process.

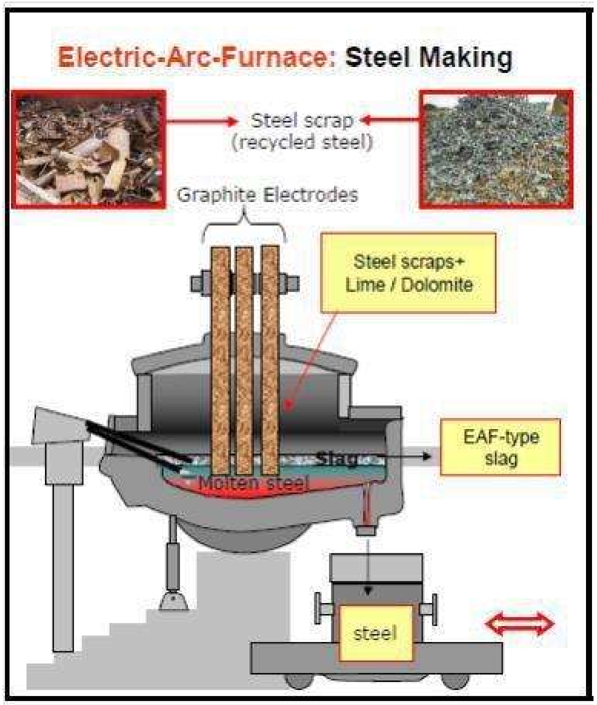


Figure 2.2: Schematic representation of the Electric -Arc- Furnace Steel Making Process (Yildrim and Prezzi, 2011)

2.3 CONARC FURNACE STEEL MAKING AND CONARC SLAG GENERATION

The name of the process CONARC sums up the fusion of the two processes (CONverter and ARCing). CONARC steel making process combines or utilizes the benefits of both the conventional top blown converter steelmaking and electric arc furnace (EAF). CONARC furnace gives flexibility for increased use of hot metal in the electric arc furnace. However, for optimizing energy recovery and maximizing productivity hot metal is used in the ratio of 45-55% remaining being scrap and DRI. CONARC Steelmaking process is divided into two stages, first stage comprises the conventional top blown **Basic Oxygen Converter while the second stage is having Electric Arc Furnace**. In the Converter Stage, the decarburization of liquid iron is carried out by blowing oxygen and subsequently the process ends with EAF Stage, where the electric energy is utilized to melt the solid charge and superheating the bath to the tapping temperature as shown in figure 2.3. During converter stage the content of carbon, silica, manganese and phosphorous are reduced during this process slag is generated, afterward during this arcing phase, the remaining solid charge material like scrap or DRI is charged into the bath to achieve the desired tapping weight of the heat. Basicity of CONARC slag is ranges between 2 to 2.5 as the generated slag is the combination of BOF and EAF process hence the CONARC steel slag can exhibit volumetric expansion higher than the EAF slag but significantly less than the BOF steel slag. Fig. 2.3 shows the CONARC steel making process.

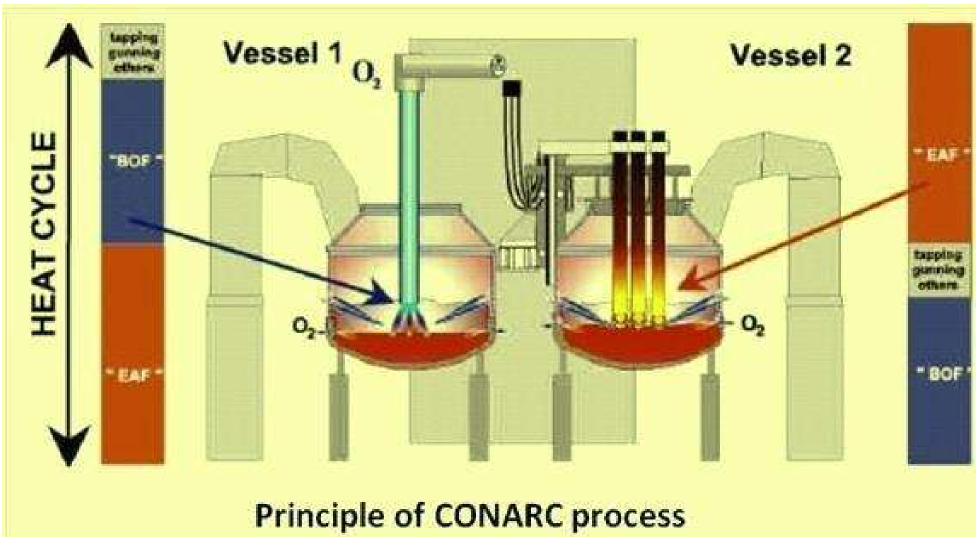


Figure 2.3: Schematic representation of CONARC Steel making process (https://aaryametallurgicals.com/brochure/Primary%20Metallurgy.pdf)

3.0 CHALLENGES IN STEEL SLAG UTILIZATION AS ROAD MAKING AGGREGATES

Steel slags due to distinct chemical and mineralogical composition exhibits different physical and mechanical attributes in comparison to natural aggregates. Although the major chemical constituents of BOF, EAF and CONARC steel slag are CaO, SiO_2, FeO, MgO and Al_2O_3 but variation in their respective concentration in a particular type of slag governs the slag intrinsic properties. These five oxides constitute around 95 % volume of oxide composition of steel slag thus responsible for major physical attributes of steel slag. Following are the broad properties of steel slag, which require treatment or processing through appropriate steel slag valorization technology for its utilization as road making aggregates:

3.1 VOLUMETRIC EXPANSION

Steel slag, which is generated as an impurity due to the charge of fluxing agent in the furnace, shows volumetric instability due to the presence of free lime and free magnesia. A steelmaking slag may contain appreciable amounts of free lime (f-CaO) and small amounts of free magnesia or periclase (f-MgO), which causes expansive self-destruction by about 100% volumetric increase due to hydration process. Natural aggregates are derived from igneous and metamorphic rock groups. Natural aggregates generally contains high amount of silica therefore does not exhibit any appreciable volumetric expansion due to hygroscopic moisture. On the contrary, steel making slag, because short refining time and high amount of limestone content, having un-dissolved lime as free CaO in the slag, which attribute appreciable volumetric changes to steel slag aggregates.

Among all three types of steel slag i.e BOF/LD, EAF and CONARC steel slag, **BOF steel slag shows high volumetric expansion** owing to presence of high CaO concentration leading to high basicity ratio i.e $(CaO + MgO)/(SiO_2 + Al2O_3)$ higher than 2.5. EAF slag due to comparatively low basicity ratio less than 2.0 does not exhibit any appreciable amount of volumetric expansion. Out of the total expected volumetric expansion in the BOF steel slag, around 80-90 % volumetric expansion (short term expansion) happens due to presence of free lime, while 10-20% volumetric expansion (long term expansion) is attributed by the free MgO. Under the effect of moisture, free lime (CaO) and magnesium oxide (MgO) in newly crushed steel slag will hydrate and turn into calcium hydroxide $Ca(OH)_2$ and magnesium hydroxide $Mg(OH)_2$ respectively, which can cause unacceptable cracks and heaves in pavement structure. Photo 3.1 shows the free lime pocket in slag aggregate while photo 3.2 shows the distress caused in bituminous layer due to volumetric expansion in slag aggregates:

Photo 3.1: Lime Pocket in Steel Slag

Photo 3.2: Heave in bituminous layer due to Volumetric expansion in slag aggregates

BOF steel slag having high volumetric expansion can cause serious detrimental effect on durability of bituminous mixes in short span of time. Photo 3.3 shows cracks in bituminous mix Marshall specimen prepared with unaged BOF Steel slag and kept in water bath at 60ºC temp. as per Marshall Mix design protocol. For potential utilization of BOF steel slag as road making aggregates, BOF steel slag are required to be aged or treated to reduce volumetric instability caused by free lime and magnesia.

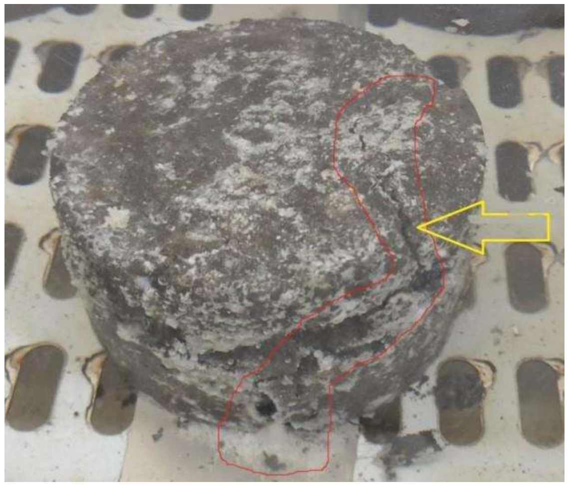


Photo3.3: Cracked Bituminous mix, Marshall Test specimens at 60^0 C temperature in water bath due to volumetric expansion of steel slag

Due to low basicity ratio EAF and CONARC steel slag, exhibits low volumetric expansion in comparison to BOF steel slag therefore does not require aging to curb volumetric expansion.

3.2 VESICULAR TEXTURE AND POROUS STRUCTURE

In comparison to natural aggregates, the microscopic surface of steel slag has pitted and vesicular texture and porous structure. The cellular or vesicular texture results from the bubbles of the gases, which have been dissolved, in the liquid slag. Vesicular texture and porous structure may lead to higher water absorption, which in turn lead to higher bitumen and cement consumption in comparison to natural aggregates. Besides that, irregular surface morphology with rough surface texture increases the surface area of aggregate for bitumen coating. A customized steel slag valorization technology comprising controlled heating if molten slag in the slag pit based on steel slag type can reduce the vesicular texture and porous structure in the slag considerably. Photo 3.4 and photo 3.6 shows the irregular vesicular texture at macroscopic level while photo 3.5 shows the porous structure at microscopic level as monitored from SEM.

Photo 3.4: Irregular and Vesicular texture

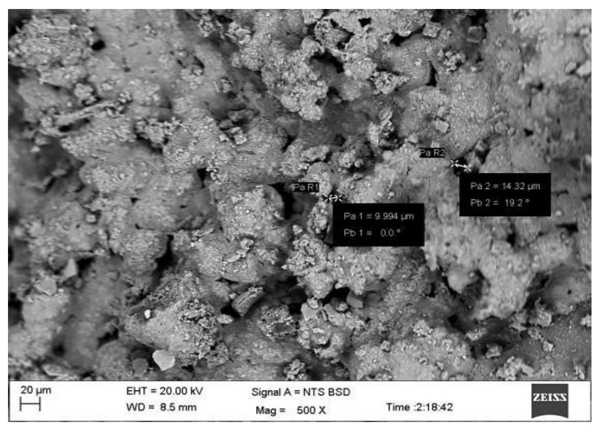


Photo 3.5: Porous Structure at Microscopic level

Controlled slow cooling of molten slag in the slag pit based on steel slag type can reduce the vesicular texture and porous structure in the slag considerably. It also controls the micro texture of the slag to produce good quality processed steel slag aggregates for road making

Photo 3.6: Porous Structure in steel slag at Macroscopic level

3.3 PROPENSITY OF HIGH PH AND HEAVY METAL LEACHATES

Steel slags may contain heavy metals such as arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, lead, mercury, nickel, selenium, thallium, vanadium, etc. at than those in most of the natural soils. Even though these metals are available as minor constituents in steel slag, possible leaching of these heavy metals into groundwater and native soil should be prevented. BOF steel slag owing to presence of high CaO can emanates high pH leachates which can make the nearby water and soil body alkaline in nature (Shen & Forsberg, 2003). These alkaline leachates can increase water pH, increased chemical oxygen demand (COD), causes oxygen depletion, increased salinity, and increased metal concentrations (Mayes and Younger, 2006) in nearby areas. High pH levels of steel slag, affects waters bodies, mainly due to the leaching of alkaline substances from steel slag into the water. Photo 3.7 and photo 3.8 shows the possible leachate contamination from unprocessed steel slag dumps in nearby soil and water bodies. Probability of leaching from the slag can be considerably reduced by developing stable mineralogical phases in the slag though controlled cooling in slag pit and further subjecting it on appropriate weathering mechanism according to steel slag type.

Photo 3.7: High pH leachate from slag dump

Photo 3.8: High pH leachate in water bodies

Figure 3.1 shows the possible movement of high pH leachate emanated from the steel slag road layers in near water aquifer and water bodies.

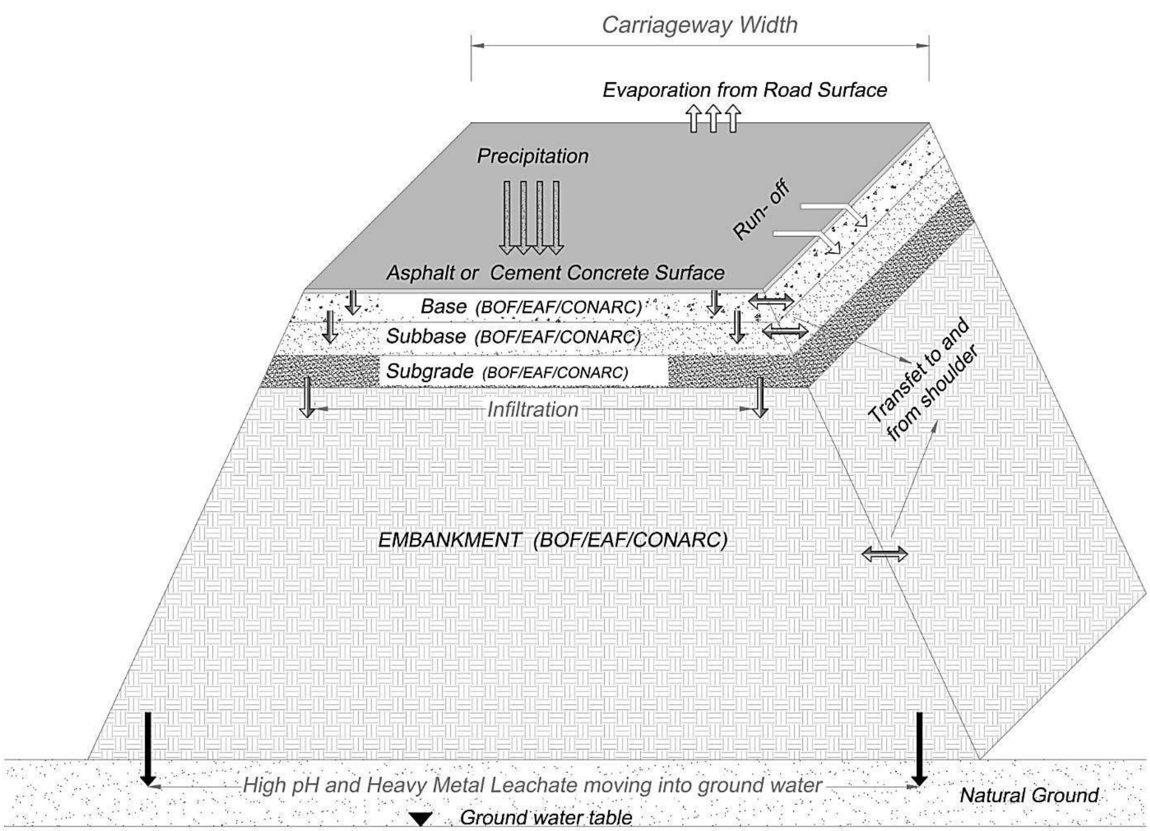


Fig. 3.1 Possible ways of contamination of ground water table through Heavy Metal and high pH Leachate

3.4 CORROSION POTENTIAL

The deterioration or disintegration of a material by a chemical or electrochemical reaction with its environment is defined as corrosion. Metals lose electrons when they react with water and oxygen, leading to the occurrence of corrosion. During tapping of steel slag from furnace part of metallic fraction goes with slag, which causes corrosion in steel slag. This metallic iron fraction can be removed through magnetic separation process. Particularly when steel slag is used in unbound applications (embankment, road bases, etc.), the corrosion potential of steel slag should be evaluated carefully. In case steel slag aggregates is to be utilized in marine environment propensity of corrosion become a critical factor hence must be evaluated carefully. Steel slag particularly LD slag being calcareous in nature produces alkaline environment in pavement layer. These elevated pH range in pavement material can increase the rate of corrosion in any metallic body coming in contact with steel slag. Figure 3.2 shows the rate of corrosion in acidic and alkaline environment, while photo 3.9 shows corrosion in BOF steel slag. Rate of corrosion increases with the increase in acidic and alkaline environment corresponding to neutral pH.

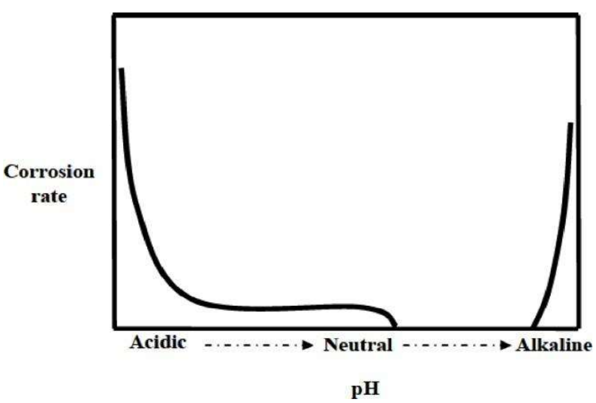


Fig. 3.2: Rate of corrosion versus pH (Scully 1990, Irem & Prezzi, 2009)

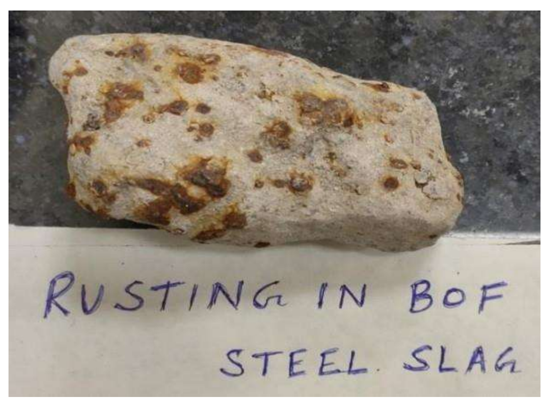


Photo 3.9: Corrosion in BOF Steel Slag

3.5 CARBONATION POTENTIAL

During the aging (weathering) process, CaO and MgO hydrates to form $Ca(OH)_2$ and $Mg(OH)_2$, along with alkaline silicates of Ca and Mg in the steel slag, these hydrated compounds can react with carbon dioxide (CO_2) from the atmosphere and/or automobile exhausts during aging in stockpiles.

This CO_2 sequestration reaction is known as "carbonation". The carbonation behavior of steel slag can be summarized as follows:

- $(Ca,Mg)SiO_3 + CO_2 \rightarrow (Ca,Mg)CO_3 + SiO_2$
- $Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$
- $Mg(OH)_2 + CO_2 \rightarrow MgCO_3 + H_2O$

Carbonation process resulted into formation of tufa-like materials on BOF slag aggregate surface which can impeded drainage characteristics of granular layers of road when incorporated as road base or sub-base. Tufa precipitation is the outcome of steel slag carbonation reactions that occurs under the bituminous surface in unbounded pavement layers. High concentrations of carbon dioxide (CO2) in the atmosphere or from automobile exhaust react with rainwater to form carbonic acid (H2CO3). This carbonic acid reacts with the hydrated lime ($Ca(OH)_2$) in the drain water to form calcium bicarbonate ($Ca(HCO_3)_2$), the solution, calcium carbonate (CaCO3) precipitates on the surface of the aggregates the form of TUFA deposition. Photo 3.10 shows the tufa formation on BOF steel slag aggregates surface due to prolong carbonation process.

Photo 3.10: Tufa formation on BOF steel slag aggregate surface

4.0 PROCESSING METHDOLOGY OF STEEL SLAG AS ROADMAKING AGGREGATES

Steel slag produced in an integrated steel plants required to be processed to develop processed steel aggregates for road making. Processing methodology of steel slag varies with the type of steel slag to develop necessary physio-chemical and engineering properties of steel slag aggregates for various road application. The following are the essential processing steps of steel slag to develop good quality processed steel slag aggregates for road application:

- Controlled Cooling
- Balling and Mechanical Breaking
- Primary Metal recovery
- Primary and Secondary Crushing
- Secondary Metal recovery
- Sizing/Screening in different sizes
- Weathering or Surface modification depending upon type of steel slag
- Stockpiling

4.1 CONTROLLED SLAG PIT COOLING

Steel slag shall be poured into the slag pit in a dedicated cooling yard from the furnace or the slag pot at a temperature of 1400^0C -1700^0C. Steel slag shall be allowed to cool in the slag pit in a controlled manner to develop micro texture in the slag. Slag cooling shall be carried out through combination of air and water sprinkling. The molten steel slag should not be subjected on rapid cooling through water as it causes the development of amorphous phase and vesicular structure in the slag aggregate. A slag heat shall be kept min. 8 to 10 hours in slag pit for cooling in case of BOF steel slag while this cooling period can be minimized to 6 to 8 hours in case of EAF and CONARC steel slag.

4.2 BALLING AND MECHANICAL BREAKING

After cooling in slag pit, large steel slag boulders shall be break in to smaller sizes through balling and mechanical breaking process. Photo 4.1 shows the balling of large size slag skull through balling action in slag yard. Balling is carried out through specially designed hydraulic rope cranes that give output of approximately 10 tonne per hour of processed slag skulls.

Photo 4.1: Balling in slag yard

Besides the balling mechanical breakers can also be used for breaking large size slag skull for metal recovery.

4.3 PRIMARY METAL RECOVERY

Steel making slag contains about 10 to 20 % metallic iron by mass and is recovered by magnetic separation. Typically, the slag skulls that are larger than 250 mm in diameter are highly metallic and are recycled as scrap. Slag fraction from 100 to 250 mm sizes are typically passes through drum type magnetic separator also known as metal recovery plant for primary metal recovery. As material reaches the drum, the magnetic field attracts and holds ferrous metallic fraction in the slag to the drum shell. As the drum revolves, it carries the material through the stationary magnetic field. The nonmagnetic material falls freely from the drum, while the metallic magnetic particles are held firmly until they are carried out of the magnetic field. The magnetic drum assembly is contained in a dustproof housing with an opening at the bottom for the discharge of both magnetic and nonmagnetic slag.

4.4 PRIMARY AND SECONDARY CRUSHING

After metal recovery steel slag of feed size 100 to 250 mm are subjected on primary crushing in jaw crusher. Jaw crushers are mainly used as primary crushers in aggregates production, and recycling applications. For primary crushing jaw opening in jaw crusher should range between 80 to 100 mm. After primary crushing approximate 40 % slag feed, will have the size between 40 to 100 mm. After primary crushing this 40 to 80 mm size slag fraction shall be subjected on secondary crushing using secondary jaw crusher or cone crusher to obtain 53 mm down aggregate fraction. Selection of secondary jaw crusher or cone/impact crusher will be based on quantum of slag generation and required output from crushing plant. Processed steel slag aggregates of following sizes are required to be produced for different road applications:

1) 40 to 50 mm
2) 20 to 40 mm
3) 10 to 20 mm
4) 5 to 10 mm
5) 0 to 5 mm

An integrated Metal recovery cum Crushing Plant can have following components to produce different size of processed steel aggregates and to remove metallic iron from steel slag:

1) Jaw Crusher
2) Metallic Magnetic Separator
3) Cone Crusher/ Secondary jaw crusher or Impact Crusher
4) Rumbler
5) Grizzly Feeder
6) Inclined Grizzly Feeder
7) Inclined/ Vibratory screens of different sizes
8) Low Intensity Magnetic Separator or Magnetic Pully
9) Loader and Dumpers

10) Rock or Mechanical Breaker

Figure 4.1 shows the typical flow chart of metal recovery cum steel slag crushing plant of 250 TPH capacity which shall be customized according to steel slag generation, slag hardness, metallic iron content, feed composition and capacity requirements.

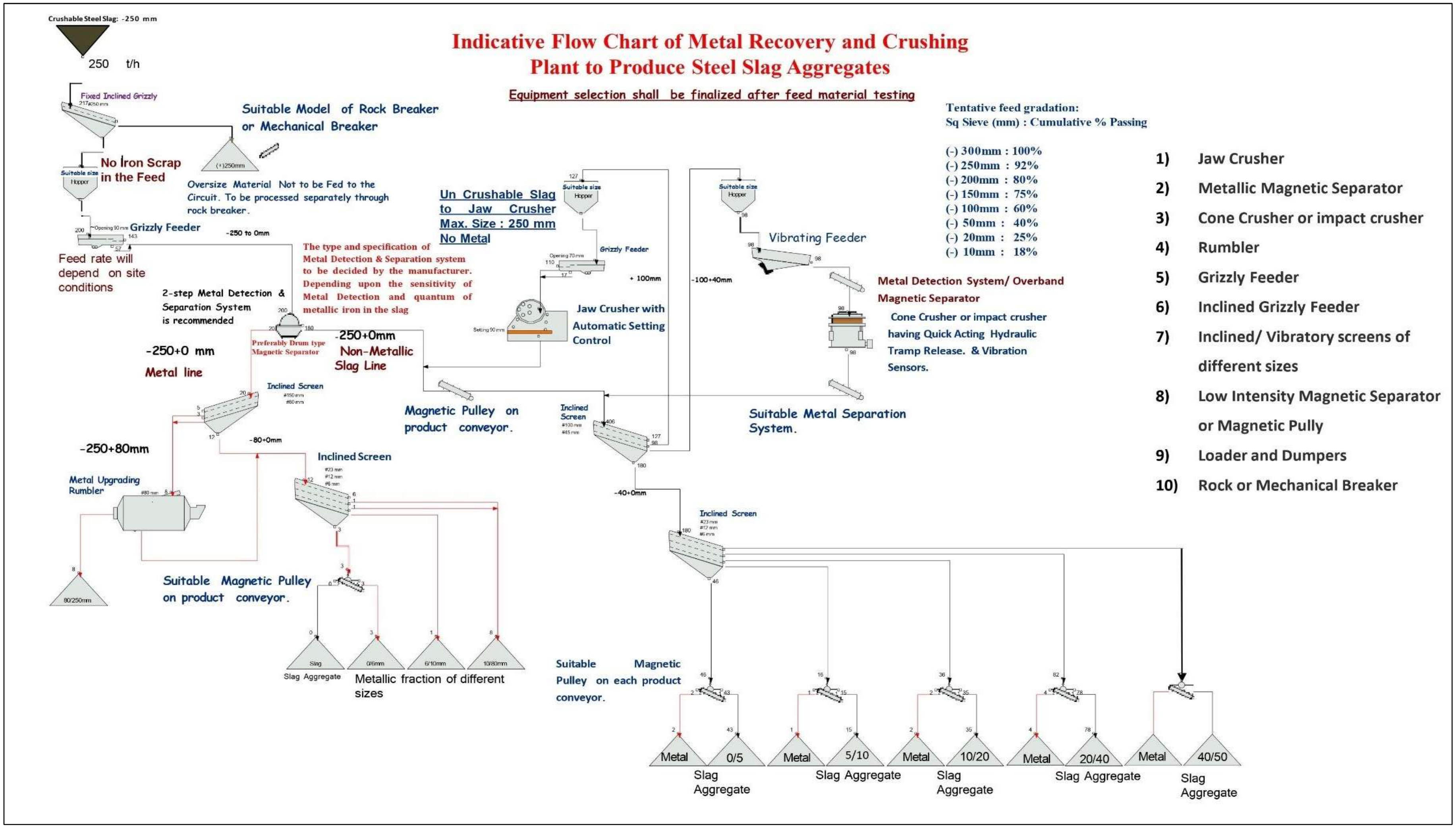


Figure 4.1: Typical Flow chart of Metal recovery cum Steel Slag Crushing plant of 250 TPH capacity

4.5 SECONDARY METAL RECOVERY

During primary and secondary crushing electromagnetic separators shall be installed on conveyor belts to maximize metallic iron recovery. Magnetic field in terms of gauss setting shall be determined according to probable metallic iron content in the slag to maximize metallic recovery. Steel slag may contain the magnetic non-metallic mineralogical phases, due care shall be taken while carrying out secondary metal recovery to distinguish non-metallic magnetic fraction with metallic magnetic fraction. Primary and secondary metal recovery will result in to 5 to 10% of metallic iron recovery which can be recycled/reused in steel furnace for steel production.

4.6 SIZING/SCREENING IN DIFFERENT SIZES

During primary and secondary crushing non-metallic steel slag fraction shall be screened in to five different sizes for road application. Different size of steel slag aggregates shall be stockpiled separately to ensure requisite gradation in the material as road aggregates. Screened slag aggregates shall have the following gradations as given in table 4.1.

Table 4.1: Gradation Requirement for Steel Slag Aggregates

IS Sieve Size in mm	Percentage of Aggregates passing through different Sieve Size				
	Nominal Size of Aggregates				
	40-50 mm	20-40 mm	10-20 mm	5-10 mm	0-5 mm
53.0	100	100	100	100	100
45.0	15-40	95-100	100	100	100
37.5	0	71-95	100	100	100
26.5	0	20-30	95-100	100	100
19.0	0	5-10	85-95	100	100
13.2	0	0	10-20	95-100	100
9.5	0	0	0	80-95	100
6.3	0	0	0	5-10	100
4.75	0	0	0	0	90-100
2.36	0	0	0	0	70-90
1.18	0	0	0	0	55-75
0.600	0	0	0	0	45-60
0.300	0	0	0	0	30-45
0.150	0	0	0	0	20-40
0.075	0	0	0	0	5-15

NOTE: Steel Slag Aggregates fractions of greater than 53 mm size due to high specific gravity and metallic content shall not be used for road applications. Prolong uses of these fractions in WMM and GSB mix can cause accelerated wear and tear in WMM Plant/Pugmill as well as road paver. Besides that, in case of BOF steel slag larger size aggregates become more prone for volumetric expansion due to entrapped free lime inside the aggregates.

4.7 STEEL SLAG TREATMENT AND AGING PROCEDURE

Following steel slag treatment techniques can be used to reduce, volumetric expansion, potential of heavy metal with high pH leaching and propensity of corrosion in the steel slag. Steel slag treatments techniques mentioned below are suggestive methods and does not restrict steel industries to use any other methods or technologies to reduce volumetric expansion, propensity of leaching and corrosion.

4.7.1 Natural Aging or Weathering

It’s a long-term process where steel slags are stockpiled for considerable long period for at least 1 to 2 years’ time, for weathering through natural agencies such as rain and temperature to accomplish hydration reaction. Stockpile time varies with slag type an entrapped free lime and magnesium oxide content. It’s an uncontrolled process which require large tract of land and considerable amount of time to reduce the volumetric instability in steel slag. Resultant products exhibit inconsistency in residual volumetric expansion as some steel slag fraction can still remain buried in the large heap and hydration reaction can remain unaccomplished in the process.

4.7.2 Accelerated Ageing or Weathering

Accelerated aging or weathering technologies are based on the accelerated hydration reaction through artificial means. Following accelerated weathering technologies can be used to reduce volumetric expansion in slag.

A) Artificial Weathering through alternate wetting and drying cycle:

Under this process steel slag stock pile are subjected on alternate wetting and drying cycle through water sprinkling to accomplish hydration reaction. Water utilized in the process can be recycled and reused for successive cycles. Stockpiles are rotated after seven days" time with the help of dosers to uniformly accomplish the hydration reaction in whole stockpiled aggregate. Around three to four months" time are required to achieved the desired degree of volumetric instability. Major limitation of the method is the requirement of large tract of land, high volume of water consumption, long time period and substantial cost of treatment.

B) Accelerated Steam Aging

In this process water steam is injected at atmospheric pressure from perforated bed and sidewalls in steel slag layered stockpile. Stock pile is covered through tarpaulin to entrap the steam within the slag mass for early accomplishment of hydration reaction. Under controlled condition appreciable reduction in volumetric expansion can be achieved in 7 to 8 Days" time. Although un-hydrated CaO and MgO pockets can still remain in treated slag in small quantity. The major limitation is high cost of treatment and requirement of large quantity of water for steam generation, beside high energy requirement for steam production. Some steel plants exposed the slag to a high-temperature steam using latent heat of slag before removing from slag pit. They cover the slag with tarpaulin before it reaches to atmospheric temperature. This high-temperature steam treatment hydrates the expansive components of steel slag before its utilization for road applications and decreases the potential swelling in the steel slag. A customized slag yard with steam aging facility can be developed according to steel slag type as shown in figure 4.2 and photo 4.2.

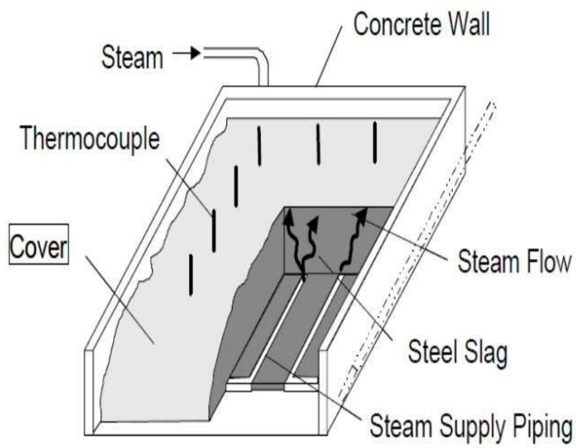


Figure 4.2: Schematic representation of Steam Aging Plant
(Nippon Steel & Sumitomo Metal Technical Report No. 109 July 2015)

Photo 4.2: Large scale steam aging facility
(Nippon Steel & Sumitomo Metal Technical Report No. 109 July 2015)

C) Pressurized Steam Aging using Autoclave

Under this method steel slag aging is carried out in a pressurized vessel which is usually an autoclave. After placement of the slag in autoclave, it is charged with steam at 0.6 to 0.8 MPa pressure and retained for 2 to 3 hours time until aging is completed. Nippon steel association in Japan is using pressurized steam aging technique for aging of steel slag as shown in figure 4.3 and photo 4.3.

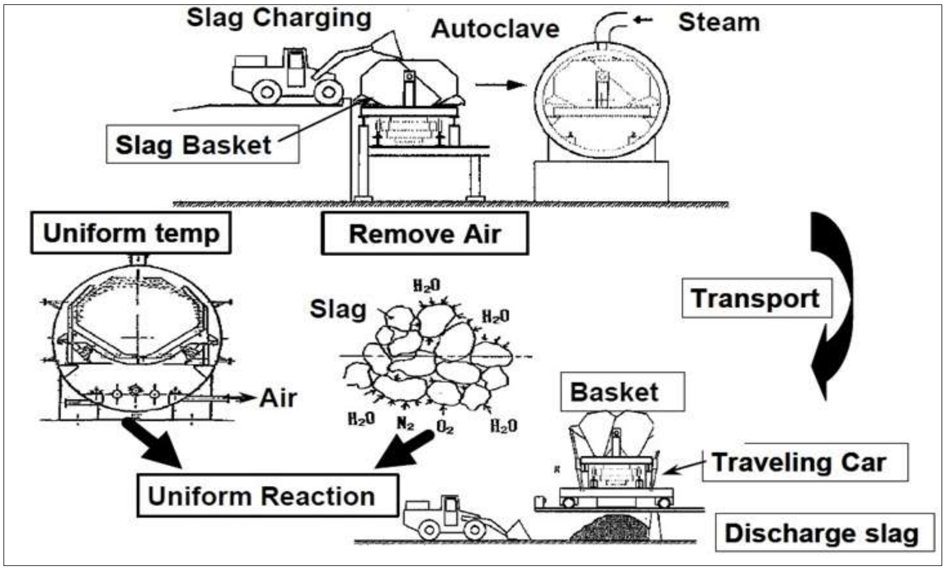


Figure 4.3: Schematic representation of Autoclave treatment

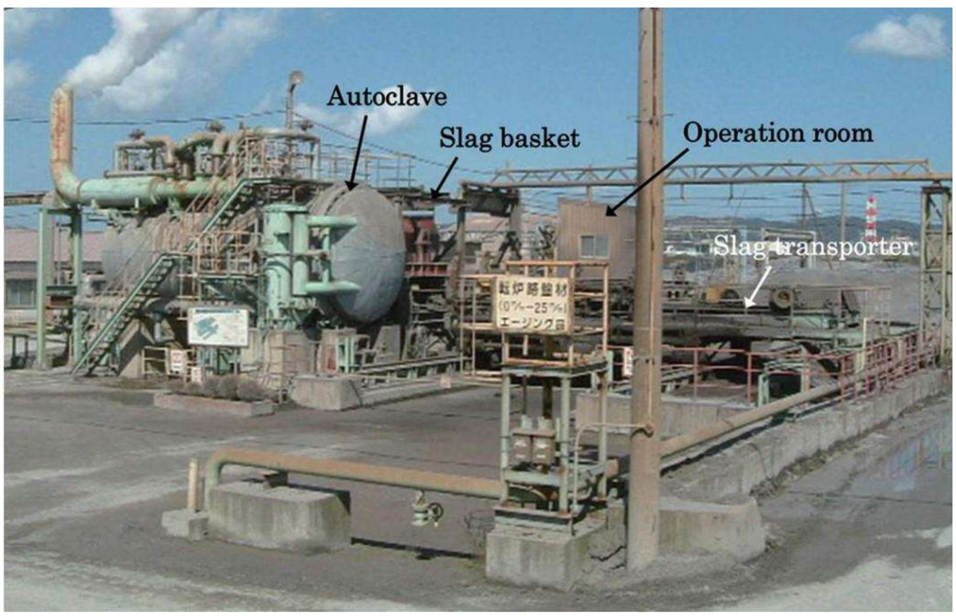


Photo 4.3: Pressurized Steam Aging plant based on Autoclave
(Nippon Steel & Sumitomo Metal Technical Report No. 109 July 2015)

4.7.3 Surface Modification

This treatment methodology is based on the principal of covering/coating the surface of steel slag with in-organic waterproofing compounds such as polymeric siloxane, Alkyl aloxy silicon compounds or organofunctional silane to prevent ingress of moisture in the slag aggregates. Composition of organic water proofing compound will vary with steel slag type and chemical composition and it will also affect its efficacy to impart hydrophobicity in the slag. This treatment process prevents hydration reaction in slag aggregate thus eliminate volumetric expansion caused by free CaO and MgO. Surface modification process also prevents the possibility of heavy metal leaching and high pH leachate as once the surface is coated no leachate can comes out. In case the aggregate is of high metallic content due to poor efficacy of magnetic separation process this treatment can still prevent the aggregates from possibility of corrosion. To treat the aggregates a solution shall be prepared using 0.5 to 1% waterproofing compound in the water. Optimum doses of solution in the water can be determined by laboratory trials to obtain water phobic characteristics in the slag aggregates. Treatment of aggregates can be carried out either by sprinkling the solution on aggregate surface or moistening the aggregates surface in the concrete mixer. After treatment aggregate shall be air dried and checked for water absorption. Post treatment aggregate will have water phobic surface and almost negligible water absorption when kept in water bath for 24 hours. Nano surface modification process treated processed steel slag aggregates of different sizes should satisfy following physical parameters as given in table 4.2.

Table 4.2: Parameters to check the efficacy of surface modification on treated Steel Slag Aggregates

Particulars	Processed Steel Slag Aggregates Size in mm				Test Method
	5-10	10-20	20-40	40-50	
Contact Angle in ^{0}Min.	125	130	130	135	Drop Shape Analyzer
Water Absorption %	< 0.5 %	< 0.2 %	< 0.1 %	< 0.1 %	IS 2386 (Part III)
Volumetric expansion %	Max. 1%				EN:1744-1
Tensile Strength Ratio %	> 95 %				AASHTO T-283

Note: 1) Surface modification of steel slag fines of 0 -5 mm size cannot be carried out uniformly due to large surface area. Hence steel fines may be treated with other treatment methods

2) For volumetric expansion test as in place of 0 to 5 mm size steel slag fraction crushed stone dust or natural sand can be utilized

4.7.4 Comparative Analysis of Different Treatment Methods

Different types of steel slag treatment methods to curb volumetric expansion are having its own benefits and limitations with varying cost implications. Table 4.3 summarizes the benefits and limitation of different steel slag treatment methodologies.

Table 4.3: Comparative Analysis of different slag treatment and aging procedures

Parameters	Different Steel Slag Treatment Methodologies				
	Natural Weathering (A)	Artificial Aging			Surface Modification (E)
		Open Yard Aging (B)	Steam Aging (C)	Pressurized Steam Aging (D)	
Efficacy of Treatment	Non-Uniform	Good	Better	Best	Best
Treatment Time	1 to 2 years	3 to 6 Months	3 to 7 Days	6 to 8 hours	10 to 12 Hours
Area Requirement (Hect.)	Very large area	1.5 to 2.	0.5 to 0.8	0.7 to 1.0	0.3 to 0.4
Capital cost	Lowest	A< **B** < C, D, E	A, B, E<**C**<D	A,B,C, E< **D**	A,B<**E**<C,D
Effect on Properties of steel slag	Volumetric Expansion Leaching	Volumetric Expansion Leaching	Volumetric Expansion	Volumetric Expansion	Volumetric Expansion Leaching Water absorption

4.8 STOCKPILING

After treatment of slag processed steel slag aggregates shall be stockpiled according to their sizes on firm drained surface to supply for different road applications. Stockpiling shall be carried out in well demarcated bins as per size of steel slag aggregates. Before supplying the aggregates for road application various quality control checks shall be carried out by the supplier as given in table 9.1 and provide the test results to the user.

5.0 PROCESSING REQUIREMENT OF DIFFERENT TYPE OF STEEL SLAG

Table 5.1 summarizes the processing requirements for different types of steel slag to produce Processed Steel Slag Aggregates for Road Making:

Table 5.1: Processing requirements for different types of steel slag

S.No.	Particulars of Processing	BOF SLAG	EAF SLAG	CONARC SLAG
1	Controlled Cooling	✓	✓	✓
2	Balling and Mechanical Breaking	✓	✓	✓
3	Primary Metal recovery	✓	✓	✓
4	Primary and Secondary Crushing	✓	✓	✓
5	Secondary Metal recovery	✓	✓	✓
6	Sizing/Screening in different sizes	✓	✓	✓
7	Weathering or Surface Modification	✓	If expansion >3%	If expansion > 3%
8	Stockpiling	✓	✓	✓

* EAF steel slag due to low basicity ratio does not exhibit volumetric expansion. Hence the EAF steel slag will not require treatment to curb volumetric expansion. CONARC steel slag depending upon Hot Metal content in the slag may exhibit volumetric expansion. If volumetric expansion in the CONRC slag is exceeding 3 % then the steel slag is required to be subjected on weathering or surface modification.

6.0 CHEMICAL COMPOSITION OF PROCESSED STEEL SLAG AGGREGATES

Chemical composition of processed steel slag aggregates depends upon the type of steel producing process, i.e. BOF, EAF and CONRAC. Different types of steel furnaces are subjected on variable type of charges (variable composition of hot metal and scrap) to produce low carbon steel thus the chemical composition of Steel Manufacturing Slag (SMS) also changes considerably with type of furnace. Chemical composition of different types of steel slag aggregates obtained from five leading steel industries in India is determined through Wave Dispersive XRF analysis and reported in table 6.1. For comparative analysis purpose chemical composition of good quality natural aggregates, obtained from igneous rock group, commonly used in road making in India is also determined and reported in Table 6.1. Processed steel slag aggregates depending upon the volumetric expansion, is required to be subjected on different types of treatment as suggested in section 4.7 before any road applications. This process causes carbonation in the slag aggregates due to hydration reaction. Steel slag sample which has been subjected on natural and artificial weathering will have higher loss on ignition. Loss on ignition of the slag aggregates shall be determined and reported along with the chemical composition. Loss on ignition will vary according to the nature of the sample. The LOI value obtained will include loss due to the oxidation of any carbonaceous matter and gain due to the oxidation of any ferrous iron present. LOI shall be determined before subjecting the sample for chemical composition analysis in XRF. LOI can be determined through Muffle furnace by keeping the slag sample between 900 to 1000^0C.

Table 6.1: Typical Chemical Composition of Processed Steel Slag Aggregates derived from different types of steel slag

Type of Steel Slag	CaO (%)	SiO_2 (%)	MgO (%)	Fe_2O_3 (%)	MnO (%)	SO_3 (%)	P_2O_5 (%)	TiO_2 (%)	K_2O (%)	Cr_2O_3 (%)	Al_2O_3 (%)	L.O.I (%)
CONARC	42.39	14.90	3.72	29.50	1.94	0.24	0.89	0.509	0.094	0.110	5.674	4.97
EAF	39.74	15.99	3.67	31.71	0.51	0.21	0.67	0.512	0.060	0.109	6.781	3.91
BOF (Source 1)	55.65	10.69	3.44	18.46	2.19	3.07	0.60	0.552	0.045	0.102	5.162	14.32
BOF (Source 2)	59.41	12.11	1.90	18.60	0.58	0.39	1.84	0.815	0.075	0.149	4.107	15.03
BOF (Source 3)	59.92	11.94	2.13	20.89	1.03	0.47	1.05	0.485	0.048	0.0586	1.935	14.83
Natural Aggregates (Igneous Rock Groups)	35.82	37.41	4.72	7.50	0.39	0.22	0.23	0.748	2.886	0.0385	10.008	11.47

*LOI: Loss on Ignition

Note:

1) High LOI value is due to the carbonation rection in BOF steel slag aggregates, LOI value will vary with the aging/weathering time with free lime and MgO content in the steel slag

2) Processed steel slag aggregates will largely have above mentioned chemical constituents. Concentration of chemical constituent will vary with steel plant

7.0 STEEL SLAG AGGREGATE REQUIREMENT FOR SIX LANE 1 KM ROAD CONSTRCUTION

An illustrative calculation of approximate quantity of processed steel slag aggregates and natural aggregates requirement for the construction of a 1 km. long six lane bituminous and cement concrete road for 100 MSA design traffic is given in Table 7.1 to 7.4. Conventional road section thickness for bituminous and cement concrete pavement are taken from IRC: 37-2018 and IRC: 58-2015 respectively. Bituminous steel slag road due to superior mechanical properties of processed steel slag aggregates and high CBR of steel slag fines, can be built with 30 to 40 % lower thickness in comparison to conventional bituminous roads for identical traffic conditions. For cement concrete steel slag road, uses of processed steel slag aggregates in subgrade are not going to impart any additional strength to the pavement except higher durability as the majority of load in cement concrete pavement is resisted through higher flexural strength or flexural rigidity of pavement quality concrete. The stresses in these pavements are transferred through slab action, as opposed to the grain-to-grain action in the flexible pavement. The volumetric requirement of processed steel slag aggregates to construct a 1 km. long road will be comparatively less than the conventional road.

Table: 7.1 Processed Steel Slag Aggregates Requirement for Construction of Six Lane Bituminous Road

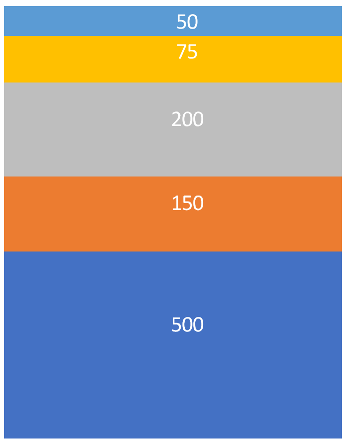
Typical Cross Section of Six Lane Road for 100 MSA Design Traffic	Width of Road including Paved Shoulder	Type of Layers	Bulk Density / Dry Density (g/cc)	Quantity of Material Required (tonne)	Volume of Material (m^3)
	26 m	**BC**- Bituminous Concrete	2.967	3664.25	1703.87
		DBM- Dense Bituminous Macadam	2.996	5564.69	2682.16
		WMM -Wet Mix Macadam	2.60	13520.0	6584.6
		GSB- Granular Sub-base	2.45	9555.0	4605.5
		Subgrade	2.3	29900.0	11232.2
All thickness in mm **Effective CBR = 30%**	Subgrade GSB WMM DBM BC **Length of Section=1km**		**Approximate Quantity of Material Required**	62203.94	26808.33

Table:7.2 Natural Aggregates requirement for Construction of Six Lane Bituminous Road

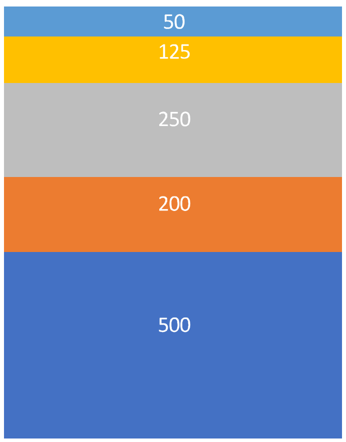
Typical Cross Section of Six Lane Road for 100 MSA Traffic	Width of Road including Paved Shoulder	Type of Layers	Bulk Density/Dry Density (g/cc)	Quantity of Material Required (tonne)	Volume of Material in m^3
	26 m	**BC**- Bituminous Concrete	2.40	2964.00	1667.3
		DBM- Dense Bituminous Macadam	2.40	7441.98	4279.1
		WMM -Wet Mix Macadam	2.11	13715.00	7907.8
		GSB- Granular Sub-base	2.06	10712.00	6159.4
		Subgrade	1.95	25350.00	12675.0
All thickness in mm Effective CBR = 8%	Length of Section=1km		**Approximate Quantity of Material Required**	60182.98	32688.6

Table:7.3 Processed Steel Slag Aggregates requirements for construction of six lane cement concrete road

Typical Cross Section of Six Lane Road for Traffic 3000 CVPD in each Direction	Width of Road including Paved Shoulder	Type of Layers	Density/Dry Density (g/cc)	Quantity of Material Required in Ton	Volume of Material in m3
	26 m	**PQC**- Pavement Quality Concrete	2.893	21713.3	9538.04
		DLC- Dry Lean Concrete	2.766	7787.0	3699.87
		GSB- Granular Sub-base	2.450	15925	7675.8
		Subgrade	2.300	29900.0	11232.2
All thickness in mm **Effective CBR = 8%**	Length of Section=1km		**Approximate Quantity of Material Required**	75325.3	32145.91

Table: 7.4 Natural Aggregate requirement for Construction of Six Lane Cement Concrete Road

Typical Cross Section of Six Lane Road for Traffic 3000 CVPD in each Direction	Width of Road including Paved Shoulder	Type of Layers	Density/Dry Density (g/cc)	Quantity of Material Required in Ton	Volume of Material in m3
	26 m	**PQC**- Pavement Quality Concrete	2.5	18763.61	10220.14
		DLC- Dry Lean Concrete	2.4	6756.6	3856.3
		GSB- Granular Sub-base	2.06	13390	7699.25
		Subgrade	1.95	25350	12675
All thickness in mm **Effective CBR = 8%**	Length of Section=1km	**Approximate Quantity of Material Required**		64260.21	34450.69

8.0 POTENTIAL APPLICATIONS OF PROCESSED STEEL SLAG AGGREGATES IN ROAD CONSTRUCTION

Table 8.1 provides the information about the potential application areas of processed steel slag aggregates as substitute of natural aggregates in road construction. Processed steel slag aggregates can be utilized as 100 % substitute of natural aggregates in various pavement layers of bituminous and cement concrete pavement.

Table 8.1: Uses of Processed Steel Slag Aggregates derived from different types of steel slag in Road Applications

S.No.	Application Ares	BOF SLAG	EAF SLAG	CONARC SLAG
1	Soil Stabilization	✓	✓	✓
2	Subgrade	✓	✓	✓
3	Granular Layers (Base Course and Sub-base course)	✓	✓	✓
4	Bituminous Layers (Binder Course and Wearing Course)	✓	✓	✓
5	Cement Concrete Layers (PQC and DLC Layers)	X*	✓	✓
6	Road Shoulders	✓	✓	✓

* BOF Steel slag due to high propensity of volumetric expansion is not suitable for utilization in cement concrete pavement in DLC and PQC layers. Plant to plant Variation in BOF steel slag aging/weathering methodology may left residual volumetric expansion in steel slag aggregates. During Large scale utilization of steel slag aggregates in cement concrete mixes, it is quite possible that some fraction of processed steel slag aggregates may have higher residual volumetric expansion, which will cause early deterioration/distress in the cement concrete pavement.

- Soil Stabilization: As mechanical and chemical stabilizers
- Subgrade: As substitute of good earth
- Granular Layers: Base Course: Water Bound Macadam, Wet Mix Macadam
- Bituminous Layers: Binder Course: Dense Bituminous Macadam

  Wearing Course: Bituminous Concrete, SDBC, SMA, MSS

- Cement Concrete Layers: Pavement Quality Concrete (PQC)

  Dry Lean Concrete (DLC)

- Road Shoulder: High strength stabilized road shoulders

9.0 PROPERTIES OF PROCESSED STEEL SLAG AGGREGATES

Processed steel slag aggregates shall be tested to satisfy engineering and environmental properties for possible utilization in different road applications. Following sub-sections provides the details for required engineering and environmental properties of processed steel slag aggregates.

9.1 ENGINEERING PROPERTIES OF PROCESSED STEEL SLAG AGGREGATES

Crushed processed steel slag aggregates of different sizes shall be tested to determine different engineering properties for various road applications. Table 9.1 provides the engineering properties and permissible limit for different type of processed steel slag aggregates along with details of testing standards.

Table 9.1: Engineering Properties of Processed Steel Slag Aggregates for Road Application

S. No.	Properties	Typical Range of Processed Steel Slag Aggregates			Permissible Limits for Processed Steel Slag Aggregates			Test Method
		BOF	EAF	CONARC	Surface Course (DBM, BC, DLC and PQC)	Base (WBM & WMM)	Sub-base (GSB)	
1	Aggregate Impact Value % (Dry Condition)	10-22	12-20	10-20	Max. 27	Max.30	Max.30	IS 2386 (Part IV)
2	Aggregate Impact Value % (Wet Condition)	12-24	14-18	12-16	NA	Max. 30	Max. 35	IS 5640
3	Los Angeles Abrasion Resistance, %	11-18	10-14	10-14	Max. 30	NA	NA	IS 2386 (Part IV)
4	Water Absorption Test %	1-2	0.5-1.5	0.5-1.5	Max. 2	Max. 2*	Max. 2	IS 2386 (Part III)
5	Specific Gravity	2.93-3.20	2.95-3.4	2.95-3.4	Permissible Range 2.9- 3.45			IS 2386 (Part III)
6	Combined Flakiness & Elongation (FI+EI) Index %	8-22	10-21	10-21	<30	<30	<30	IS 2386 (Part I)
7	Soundness Test - Sodium Sulphate in %	0.2-1.8	2-4	2-4	< 12	< 12	< 12	IS 2386 (Part V)
	Magnesium Sulphate in %	0.3-2.1	3-5	3-5	< 18	< 18	< 18	
8	Stripping Value Test % (Bitumen coating retention)	98-99	99-99.5	99-99.5	Min. Retained coating 95	NA	NA	IS 6241
9	Iron unsoundness ** %	Nil	Nil	Nil	< 1	< 1	< 1	IS 383(Annexure D)
10	Iron Stain Index Test*** (Staining from Iron compound)	0-40	0-40	0-40	< 60***	NA	NA	ASTM C 641-07
11	Volumetric Expansion Test, %	1-2	0.8-1.40		< 3			EN:1744-1

* If water absorption value exceeds 2 %, then soundness and aggregate impact value (in wet condition) tests are required to be carried out for potential utilization of slag aggregates in WMM, WBM and GSB Mixes. In case slag aggregate qualify soundness and wet aggregates impact value tests despite high water absorption same shall be reported and utilized for WMM, WBM and GSB applications.

** Iron unsoundness test shall be carried out on 20 to 40 mm and 40 to 60 mm size aggregates as per IS 383 while iron stain index test shall be carried out on 10 mm size steel slag aggregates. Both tests are required to be performed on aged or treated steel slag aggregates samples to assess the suitability of aggregates for road application.

***In case stain index is 60 or higher, steel slag aggregates shall be rejected when the deposited stain is found upon chemical analysis (as per ASTM C 641-07) to contain an iron content expressed as $Fe2O_3$ equal to or greater than 1.5 mg./ 200 g of sample.

Note:

DBM: Dense Bituminous Macadam, BC: Bituminous Concrete, PQC: Pavement Quality: DLC: Dry Lean Concrete, WBM: Water Bound Macadam, WMM: Wet Mix Macadam, N A : Not Applicable

10.0 ENVIRONMENTAL SAFETY

Processed steel slag aggregates, should be tested at producer or supplier end to rule out the possibility of any heavy metal and high pH leaching. User of the processed steel slag aggregates shall also get it tested independently before its utilization in subgrade, subbase, basecourse, binder course and wearing course of bituminous and cement concrete pavement.

10.1 ASSESSMENT OF POSSIBILITY OF HEAVY METAL LEACHING

Processed steel slag aggregates shall be tested for possibility of heavy metal/hazardous substances leaching before supplying for road applications. TCLP or Toxicity Characteristic Leaching Procedure is a chemical analysis process used to determine the presence of hazardous elements in the waste. TCLP test is a batch type test. The batch tests involve mixing of size-reduced waste with extraction solution and agitating in closed container. These tests generally are performed for a short period of time (typically for hours or days) and therefore are often called short -term tests. The main differences among these tests are leaching solution, liquid to solid (L/S) ratio, and number and duration of extraction. L/S ratio for the TCLP analysis shall be kept 10 for one stage batch test. Particle size distribution of solid waste also has significant impact on the leachability of the trace element therefore TCLP test shall be carried out on all five sizes of aggregates as stipulated in Table 4.1. Probability of heavy metal leching from the processed steel slag aggregates can be ruled out if the steel slag aggregates are found safe in TCLP testing as per US **Environmental protection Agency (EPA) method 1311**, which involves following procedure.

- Sample preparation for leaching
- Sample leaching
- Preparation of leachate for analysis
- Leachate analysis

The analysis of leachate can be carried out through two methods i.e. **ICP-MS (Inductively coupled plasma mass spectrometry) and ICP-OES (Inductively Coupled Plasma Optical Emission Spectroscopy).** Table 10.1 shows the test results obtained through ICP-MS technique and permissible limits as per MoEF, govt. of India Hazardous and other wastes (management and transboundary rules 2016):

Table10.1: Typical Test Results of processed Steel Slag Aggregates as Tested as per- EPA 1311, protocol using ICP-MS technique

S. No.	Name of Hazardous Element	Size of Steel Slag Sample			Permissible Limits in ppb as per Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016 (Schedule II)
		10-40 mm	1-4 mm	< 1 mm	
		Measurement unit in ppb (parts per billion)			
1	**Arsenic As75**	∨bdl	∨bdl	∨bdl	5000
2	**Silver Ag107**	0.027	2.11	∨bdl	5000
3	**Barium Ba138**	225	63.2	103	100000
4	**Beryllium Be9**	∨bdl	∨bdl	0.833	750
5	**CadmiumCd111**	0.262	0.0545	0.217	1000
6	**Chromium Cr52**	12	12.5	17.6	5000
7	**Cobalt Co59**	2.68	2.1	2.78	80000
8	**Copper Cu63**	∨bdl	1.14	∨bdl	25000
9	**Nickel Ni60**	30.76	19.56	25.86	20000
10	**Molybdenum Mo98**	0.0083	4.57	0.109	350000
11	**Lead Pb208**	0.84	∨bdl	∨bdl	5000
12	**Selenium 82**	4.46	1.55	2.53	1000
13	**VanadiumV51**	∨bdl	∨bdl	∨bdl	24000
14	**Zinc Zn66**	27.6	3.18	10.1	250000
15	**Manganese A6**	8739	8508	8994	10000

*∨bdl = below detection level

** Any other known hazardous element in the furnace feed or detected in chemical composition analysis of steel slag should be included in above list for TCLP analysis.

10.2 ASSESSMENT OF POSSIBILITY OF HIGH PH LEACHATE

Untreated BOF steel slag can emanate highly alkaline (pH>9) leachates in nearby water bodies and sub-soil. pH measurement of processed steel slag aggregates shall be carried out as per US EPA SW-846 Test method 9045 D. Leachate for pH determination shall be extracted at L/S ratio of 1. According to the US EPA's rules, if waste pH is greater than or equal to 12.5, or less than or equal to 2, this waste is reckoned as corrosive material. Table 10.2 provides the range of pH of processed steel slag aggregates obtained through different types of steel slag along with the pH of silicious natural aggregates for comparative purpose.

Table10.2: Typical pH values of processed steel slag aggregates and permissible pH range

Particulars	BOF Steel Slag Aggregates (mm)			EAF Steel Slag Aggregates (mm)			CONARC Steel Slag Aggregates (mm)			Siliceous Natural Aggregates (mm)		
	0-5	5-10	10-20	0-5	5-10	10-20	0-5	5-10	10-20	0-5	5-10	10-20
pH value observed	11.57	11.66	11.66	9.28	9.58	8.98	9.01	8.95	9.23	7.58	7.58	7.58
Permissible pH range	3 – 12.0											

Note: In case steel slag aggregates are not satisfying the prescribed pH limits when tested as per US EPA SW -846 Test protocol 9045 D, it should be subjected on appropriate treatment process as stipulated under section 4.7.

11.0 FREQUENCY OF TESTING

Table 11.1 provides the suggested testing frequency of different sizes of processed steel slag aggregates at the producer end for different sizes of steel slag aggregates derived from different type of steel slag.

Table11.1: Frequency of Testing for Different type of Processed Steel Slag Aggregates

Properties	Processed Steel Slag Aggregates			Testing Frequency
	BOF/LD	EAF	CONARC	
Aggregate Gradation	All size aggregates	All size Aggregates	All Size Aggregates	Per 25000 tons
Aggregate Impact Value (Dry Condition)	10-20 mm	10-20 mm	10-20 mm	Per 100000 tons
Los Angeles Abrasion Resistance	All size aggregates	All size aggregates	All Size Aggregates	Per 100000 tons
Water Absorption Test	Coarse Aggregates	Coarse Aggregates	Coarse Aggregates	Per 50000 tons
Specific Gravity	All size aggregates	All size aggregates	All Size Aggregates	Per 50000 tons
Combined Flakiness & Elongation (FI+EI) Index	Coarse Aggregates	Coarse Aggregates	Coarse Aggregates	Per 100000 tons
Soundness Test - Sodium Sulphate	All size aggregates	All size aggregates	All Size Aggregates	Per 100000 tons
Magnesium Sulphate	All size aggregates	All size aggregates	All Size Aggregates	
Stripping Value Test (Bitumen coating retention)	10-20 mm	10-20 mm	10-20 mm	Per 100000 tons
Stain Index (Staining from Iron compound)	0 to 5mm 5 to 10 mm	0 to 5mm 5 to 10 mm	0 to 5mm 5 to 10 mm	Per 50000 tons
Iron unsoundness test	20 to 40 mm 40 to 60 mm	20 to 40 mm 40 to 60 mm	20 to 40 mm 40 to 60 mm	Per 100000 tons
Volumetric Expansion	0 to 5 mm 5 to 10 mm 10 mm to 20 mm	0 to 5 mm 5 to 10 mm 10 mm to 20 mm		For EAF and CONARC Per 50000 tons FOR BOF/LD Slag Per 5000 tons
TCLP Test	All size aggregates	All size aggregates		Per 100000 tons
pH Test	All size aggregates	All size of aggregates		Per 50000 tons
Chemical Composition Analysis using XRF	All Size Aggregates	All Size Aggregates		Six Months

Note:

1) TCLP test shall be carried out on every four-month basis irrespective of above suggested testing frequency. TCLP test is also mandatory when the significant changes in furnace feed i.e. iron ore and steel scrap source and furnace chemistry is noticed in the steel plants.

2) Above mentioned tests and testing frequency stipulated in Table 9.1, are required at supplier or manufacturer end to supply processed steel slag aggregates for various road applications and does not supersede any statutory requirement laid down by Central Pollution Control Board, State Pollution Control Board and any other government agency for steel slag handling and utilization.

12.0 QUALITY CERTIFICATE AND COST OF TESTS

The producer/manufacturer shall satisfy himself that the Processed Steel Slag Aggregates complies with the requirements of these guidelines and, if requested, shall provide test certificates stipulated in table 11.1 to the user agency. Producer/Manufacturer should also furnish an independent technical audit report to user agency confirming the adoption of Steel slag processing methodology stipulated in Section 4.0 of these guidelines to develop processed steel slag aggregates.

User or construction agency shall also get it done the independent testing of supplied processed steel slag aggregates from recognized R&D lab or institution to validate the test results.

A sample test certificate, which shall be provided by the manufacturer of processed steel slag aggregates to the user agency is given below.

SAMPLE TEST CERTIFCATE

Name of the Steel Plant/ manufacturer: **Date of issue of test certificate:**

Address: **Type of Processed Steel Slag Aggregates:**

Name of user agency to whom test certificate is issued:

Properties Tested	Testing Standard followed	Test Results
Aggregate Gradation	All Size aggregates	Percentage passing
Aggregate Impact Value (Dry Condition)	10-20 mm	%
Los Angeles Abrasion Resistance	IS 2386 (Part IV)	%
Water Absorption Test	IS 2386 (Part III)	%
Specific Gravity	IS 2386 (Part III)	Tested Value
Combined Flakiness & Elongation (FI+EI) Index	IS 2386 (Part I)	%
Soundness Test - Sodium Sulphate Magnesium Sulphate	IS 2386 (Part V)	%
Stripping Value Test	IS 6241	Retained coating in %
Stain Index (Staining from Iron compound)	ASTM C 641-07	Index value
Iron unsoundness test	IS: 383-2016	Value
Volumetric Expansion	EN:1744-1	%
TCLP Test	US EPA-1311	As per table 10.1 with date of test
pH Test	US EPA SW-846 Test method 9045 D	As per table 10.2 with date of test
Chemical Composition Analysis using XRF	Through WD XRF	As per table 6.1 with date of test

(Authorized Signatory)

13.0 UNIT RATE OF PROCESSED STEEL SLAG AGGREGATES

Steel industries should ensure the availability of processed steel slag aggregates at best competitive market rates at par or below the prevailing market rate of crushed stone aggregates to user agency for **utilization as substitute of natural crushed stone aggregates** in road construction. As the construction of Steel Slag Road will require large quantity of processed steel slag aggregates hence the user or construction agency must enter into specific contract agreement with supplier/manufacture for supply of desired quantity of processed steel slag aggregates at specific unit rate in stipulated time period mentioned in the agreement. Supplier/Manufacturer/Steel Industries shall ensure the un-hindered supply of processed steel slag aggregates to the user agency for road construction as per the provision of contract agreement and should not divert the steel slag for any other purposes/ applications before the completion of contract.

As the objective of these guidelines to facilitate waste steel slag utilization in road construction hence unit price of the "**Processed Steel Slag Aggregates**", derived from different types of steel slag **shall not exceed** the market price of the "**Natural Crushed Stone Aggregates**" on ex work basis in the area/location where the steel plants are situated. Steel Industries can determine the **maximum unit rate of the processed steel slag aggregates for commercial production**, on ex work basis, by maintaining the parity with the unit rates of crushed natural stone aggregates. Unit rate of crushed natural aggregates can be determined with the **Schedule of Rates (SOR)** issued by Public Work Department of respective states where the Steel Plants are located or Schedule of Rate issued by the Central Public Department of Govt. of India. These SOR are revised on time-to-time basis by state PWD‟s and CPWD to accommodate price escalation owing to time and inflation.

Material unit rate of different types of Crushed Stone Aggregates as obtained from Delhi Schedule of Rates, 2021, Vol. 1 of CPWD is given below in table 13.1 for reference purpose.

Table 13.1: Material unit rate of Crushed Stone Aggregates as per Delhi Schedule of Rates

Code No.	Description	Unit	Basic rate in INR as on or before 01.04.2021 in Delhi Schedule of Rate
1	Stone Aggregate (single size): 50 mm nominal size	cum	1000
2	Stone Aggregates (single size): 40 mm nominal size	cum	1300
3	Stone Aggregates (single size): 25 mm nominal size	cum	1350
4	Stone Aggregates (single size): 20 mm nominal size	cum	1400
5	Stone Aggregates (single size): 12.5 mm nominal size	cum	1350
6	Stone Aggregates (single size): 10 mm nominal size	cum	1350
7	Stone Aggregates (single size): 06 mm nominal size	cum	1400

Material unit rate of different types of Crushed Stone Aggregates as obtained from **Common Schedule of Rates issued by Govt. of Andhra Pradesh** for the year 2022-23 is given below in table 13.2 for reference purpose.

Table 13.2: Material unit rate of Crushed Stone Aggregates as per Common Schedule of Rates issued by Govt. of Andhra Pradesh

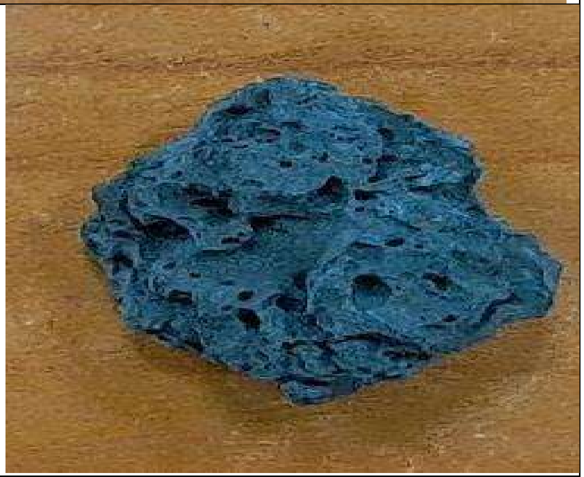
Code No.	Description	Unit	Schedule of Rate in INR for 2022-23
1	Stone Aggregate (single size): 63 mm to 45 mm	cum	761
2	Stone Aggregates (single size): 40 mm nominal size	cum	965
3	Stone Aggregates (single size): 25 mm nominal size	cum	1501
4	Stone Aggregates (single size): 20 mm nominal size	cum	1565
5	Stone Aggregates (single size): 13.2/12.5 mm nominal size	cum	1260
6	Stone Aggregates (single size): 10 mm nominal size	cum	1070
7	Stone Aggregates (single size): 06 mm nominal size	cum	865

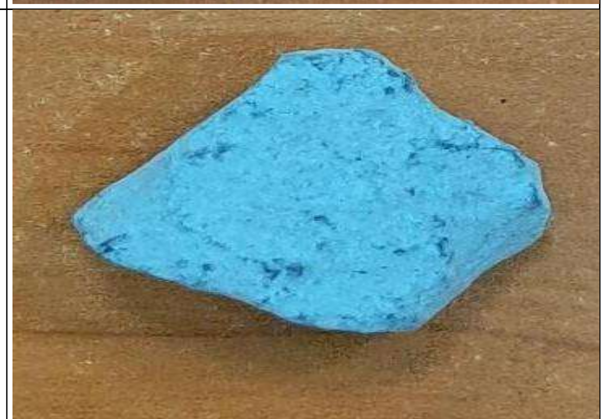
Note: These rates are exclusive of GST, carriage charges, duties and contractor profit etc.

14.0 VISUAL ASSESSMENT GUIDE FOR IDENTIFICATION OF PROCESSED STEEL SLAG AGGREGATES

Table 14.1 provides the information about the processed steel slag aggregates that what should be the visual appearance of steel slag aggregates after processing for the utilization in road construction.

Table 14.1: Visual Assessment Guide for Identification of Processed Steel Slag Aggregates

S. No.	Physical Appearance	Type of Slag	Colour	Remark	Picture
1	**Rusty (**Brown corrosion spots on the surface**)**	BOF	Milky White (Rust)	Not Acceptable	
2	**Vesicular** (Extensive surface voids covering approx. 50 % or more surface area**)**	BOF	Milky White	Not Acceptable	
3	**Vesicular** (Extensive surface voids covering approx. 50 % or more surface area**)**	EAF	Dark Grey	Not Acceptable	

4	**Cubical Angular**	EAF	Dark Grey	Acceptable	
5	**Cubical Angular**	BOF	Milky White	Acceptable	
6	**Angular**	CON ARC	Light Grey	Acceptable	
7	**TUFA Deposition (**Aggregates showing TUFA deposition on surface when keeping dip in water bath for 7 days)	BOF	Milky White	Not Acceptable	

15.0 PAVEMENT DESIGN PARAMETERS FOR STEEL SLAG ROAD

Following pavement design parameters as given in table 15.1 can be adopted for design of steel slag road built using processed steel slag aggregates, in all layers of flexible pavement as 100 % substitute of natural aggregates.

Table 15.1: Pavement Design Parameters for Steel Slag Road built using slag aggregates

S. No.	Particulars	Indicative Design Values with Processed Steel Slag Aggregates	Indicative Parameters given in IRC37: 2018 with Natural Aggregates
1	Design CBR of Subgrade (Four Days Soaked)	Min. 30 %	Max. 15 %
2	Design Elastic Modulus of Subgrade layer	Min. 600 MPa	Max. 100 MPa
3	Design Elastic Modulus of Granular Layers (WMM +GSB)	Min.1000 MPa	300-500 MPa
4	Resilient Modulus of Bituminous Layers (DBM+ BC) for VG 40 bitumen at 35ºC	2500 to 3000 MPa	As per IRC: 37

Notes:

1) Four days soaked CBR value of steel slag fines (< 4.75 mm) ranges between 35 % to 70 % for different types of steel slag i.e. EAF, BOF and CONARC. Accordingly, a conservative value of 30 % can be taken for pavement design for steel slag road to be built using processed steel slag aggregates.

2) Field modulus of steel slag subgrade and granular layers are found considerably higher than the minimum design value of 600 MPa and 1000 MPa as recommended in table 15.1. High modulus values are owing to higher specific gravity of material and cementitious properties in steel slag due to carbonation reaction in granular layers. Although a conservative modulus value is recommended for pavement design due to limited availability of field data.

3) Field modulus of subgrade and granular layer can be measured/ verified using cyclic plate load test as per IS: 5249-1995 & IS 1888: 1982. Field modulus value can also be measured by carrying out FWD test. To back calculate the modulus value using FWD deflection data, seed modulus can be taken as per table 15.1

4) Pavement design can be carried out as per IRC: 37-2018 by considering the design modulus mentioned in table 15.1.

5) Steel slag fines < 9.5 mm sieve can be utilized as 100 % substitute of good earth or fine aggregates in subgrade construction. Thickness of steel slag subgrade built using steel slag fines should not be less than 300 mm.

6) For bituminous pavement minimum thickness of WMM and GSB layers in any case shall not be less than 150 mm irrespective of design traffic and design CBR of subgrade.

7) Minimum thickness of DBM and BC to be built with processed steel slag aggregates shall not be less than 50 mm and 40 mm respectively for roads having design traffic < 50 MSA.

8) Minimum thickness of DBM and BC layer for road having design traffic between 50 to 100 MSA are 75 mm and 50 mm respectively.

9) Above-mentioned minimum layer thickness of bituminous pavement can be utilized only when the subgrade is built with the processed steel slag aggregates.

16.0 BITUMINOUS MIX DESIGN PARAMETERS

Steel Slag bituminous mixes show considerably higher stability in comparison to bituminous mixes prepared with natural aggregates. Following mix design parameters given in table 16.1 and table 16.2 shall be utilized to carry out mix design as per Asphalt Institute Manual MS-2 using Marshall Method of Mix Design for binder course DBM-Type 1 and 2 and wearing course, BC- Type 1 and 2.

Table16.1: Mix Design Criteria for Bituminous Mixes Dense Graded Bituminous Macadam and Bituminous Concrete

S. No.	Properties	Viscosity Grade Paving Bitumen for Steel Slag Road Application	Viscosity Grade Paving Bitumen in MoRTH
1	Compaction Level	75 Blows on each side of Specimen	75 Blows on each side of Specimen
2	Minimum Stability (kN at 60° C)	15	9
3	Marshall Flow (mm)	2-6	2-4
4	Marshall Quotient	3-6	2-5
5	Air Voids %	3-5	3-5
6	Voids Filled with Bitumen (VFB) %	65-75	65-75
7	Coating of Aggregate Particle	95% Minimum	95% Minimum
8	Tensile Strength Ratio (%)	80	80
9	Void in Mineral Aggregate (VMA) %	Minimum % VMA are set out in Table 3	Minimum % VMA are set out in Table 3
10	Type of Bituminous Binder	1) VG 40 and Modified Bitumen for wearing course and binder course 2) VG 30 grade bitumen is recommended to be utilized in binder course in the areas where avg. annual pavement temp. < 35^0C	

Table16.2: Minimum Percent Voids in Mineral Aggregate (VMA-MoRTH 2013)

Nominal Maximum Particle Size (mm)	Minimum VMA Percent Related to Design Percentage Air Voids		
	3.0	4.0	5.0
26.5	11.0	12.0	13.0
37.5	10.0	11.0	12.0

Note:

1) Minimum Binder content % by mass of total mix as recommended in MoRTH specification for DBM mixes can be further reduced corresponding to higher specific gravity of steel slag aggregates. Although in any case minimum binder content shall not be less than 3.5 % for DBM-1 and 4 % for DBM-2 for bituminous mixes intended to be utilized as binder course.
2) Minimum binder content for bituminous concrete mixes is 4.5 % for BC-1 and 5.0 % for BC-2.
3) In case of BOF steel slag, 4.75 mm down slag material should not be used in the bituminous mixes due to high volumetric expansion and lime content.

17.0 PARAMETERS FOR SUB GRADE, SUB BASE AND BASE COURSE

Granular sub-base is the lowest foundation layer of the pavement which distributes load on the pavement while facilitating drainage from the pavement and preventing it from frost. The base course layer is placed on the top of sub-base but directly underneath the wearing course layer. It serves variety of purpose besides acting as load bearing and strengthening component of the pavement. Following sub-sections provided the gradation and design parameters for steel slag based sub-base and base course.

17.1 STEEL SLAG AGGREGATE FOR SUB GRADE

Processed steel slag aggregates passing from 9.5 mm sieve and satisfying the requirement of table 17.1 can be utilized as 100 % substitute of good earth or granular material for the construction of subgrade. Steel slag fines are largely non plastic in nature thus plastic limit of these material can not be determined. Plasticity can be seen only when it's contaminated with soil in slag yard or steel slag crushing facility.

Table 17.1: Material characteristics for steel slag subgrade

S. No.	Properties	Results
1	Specific Gravity	2.6-3.2
2	Plasticity Index	Non plastic
3	CBR Value (after 4 days soaking)	Min. 30%
4	Volumetric Expansion (as per EN:1744-1)	< 3%
5	Percentage passing from 75-micron sieve	< 15 %

* To carry out volumetric expansion test on subgrade material fines, it shall be tested as per its original gradation intended to be utilized for subgrade construction

17.2 STEEL SLAG AGGREGATES FOR SUB-BASE

Processed steel slag aggregates intended to be utilized in sub-base shall meet out the following gradation and physical property requirements as given in table 17.1 and 17.2.

Table 17.1: GSB Gradation with Processed Steel Slag Aggregates

IS Sieve Size	Percent Weight Passing (IS Sieve)					
	Grade I	Grade II	Grade III	Grade IV	Grade V	Grade VI
53 mm	100	100	100	100	100	100
26.5 mm	55-90	70-100	55-75	50-80	55-90	75-100
9.5 mm	35-65	50-80	-	-	35-65	55-75
4.75 mm	25-55	40-65	10-30	15-35	25-50	30-55
2.36 mm	20-40	30-50	-	-	10-20	10-25
0.85 mm	-	-	-	-	2-10	-
0.425 mm	10-15	10-15	-	-	0-5	0-8
0.075 mm	<5	<5	<5	<5	-	0-3

Note: Steel Slag Aggregate larger than 53 mm size are found to be of very higher unit weight due to high metallic iron and FeO content thus difficult to lay with conventional road machineries and equipment's. Besides that, + 53 mm size aggregates are more prone for corrosion and may have residual volumetric expansion. Hence the max. size of processed steel slag aggregates for GSB application shall be restricted to 53 mm.

Processed steel slag aggregates shall satisfy the physical properties as stipulated in Table 9.1 for potential utilization in GSB Layers. Apart from that additional requirements which is to be checked by the users/ road construction agencies are as follows.

Table 17. 2: Additional Physical Requirements for GSB Mix

S. No.	Properties	Permissible Limits	Test Methods
1	Liquid Limit % (Material passing 425 micron)	Max. 25	IS 2720 (Part 5)
2	Plasticity Index (Material passing 425 micron)	Max. 6	IS 2720 (Part 5)
3	4 Days Soaked CBR at 98 % dry density	Min. 60	IS 2720 (Part 5)

Note: Steel Slag GSB mix being calcareous in nature has the tendency to bind with time. After 5 to 6 months' time GSB layer will get further stabilized and will have enhanced strength.

17.2 STEEL SLAG AGGREGATES FOR BASE COURSE

Processed steel slag aggregates satisfying the engineering properties as stipulated in Table 9.1 and meeting out the environment safety parameters can be utilized as 100% substitute of natural aggregates in WBM and WMM Mixes for construction of base course. For gradation, mix preparation and construction methodology clause 404 and 406 of MoRTH Specifications for Road and Bridge work, 5th revision, shall be used respectively. In case of WBM mixes maximum size of processed steel slag aggregates shall be restricted to 53 mm. Accordingly grading no. 2 of WBM mix can be utilized for the construction of base course layer in bituminous pavement using processed steel slag aggregates. Steel slag fines meeting out the requirement of table 9.1 can be utilized as screening material to fill the voids of coarse aggregates in WBM layer.

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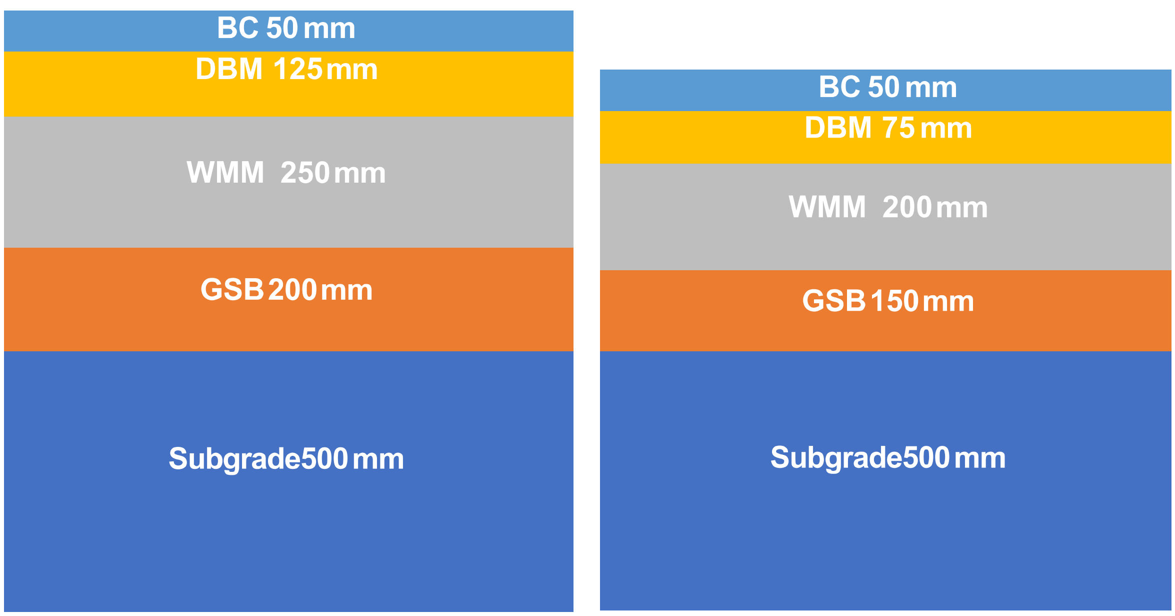
ANNEXURE-1

CASE STUDY- 1

INDIA'S FIRST STEEL SLAG ROAD SECTION CONNECTING NH -6 to HAZIRA PORT

India's first steel slag road connecting NH-6 to Hazira Port was built in April 2022 under CSIR- CRRI technological guidance using processed EAF steel slag aggregates in all layers of flexible pavement. Around 1 lakh tonne processed EAF steel slag aggregates were developed at Arcelor Mittal Nippon Steel India Limited, Hazira plant and utilized as 100% substitute of natural aggregates in subgrade, granular sub-base, base course and bituminous layers of flexible pavement. This 1 km long six lane bituminous road is designed for 100 MSA design traffic for 20-year design life and built with 32 % reduced thickness in comparison to prescribed thickness in IRC: 37:2018 for 100 MSA Design traffic and 8 % CBR subgrade. Processed EAF Steel Slag aggregates were also utilized for construction of road shoulder and median



(i) Natural Aggregate Road Section (ii) Steel Slag Road Section with Reduced Thickness

Figure A.1: Cross-Section of Natural Aggregates and Steel Slag Road Built at Hazira, Surat

Photo A.1: Aerial view of Six Lane Bituminous Steel Slag Road built at Hazira Surat using processed EAF Steel Slag Aggregates

Photo A.2: Inauguration of Hazira Steel Slag Road by Hon'ble Union Minister of Steel Shri R.C.P. Singh in June 2022

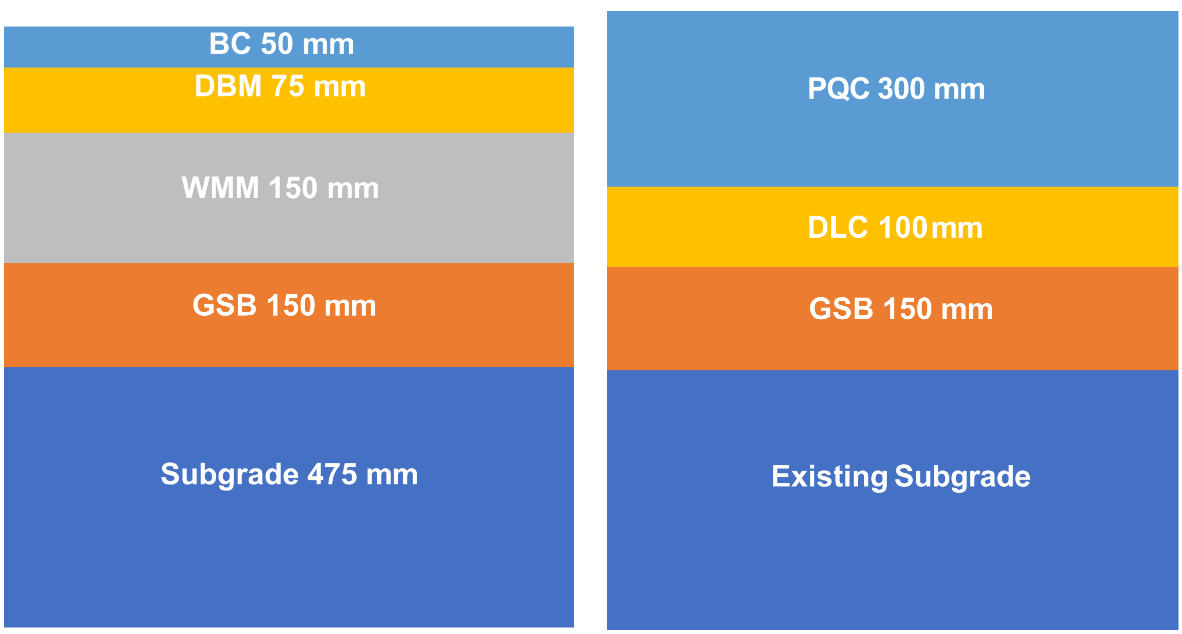
ANNEXURE-2

CASE STUDY- 2

INDIA'S FIRST NATIONAL HIGHWAY STEEL SLAG ROAD SECTION ON NH-66

(Mumbai-Goa National Highway)

India's first national highway steel slag road section on NH-66 was built in June 2023 under CSIR-CRRI technological guidance using processed CONARC steel slag aggregates in all layers of flexible and rigid pavement. Around 80000 tons of Processed CONARC steel slag aggregates developed at JSW Steel, Dolvi plant were utilized as 100% substitute of natural aggregates in subgrade, granular sub-base, base course and wearing course in flexible and rigid pavement. Bituminous road section was designed for 75 MSA design traffic and built with 28 % reduced thickness in comparison to conventional asphalt road thickness prescribed in IRC:37 for 62 MSA design traffic.



(i) Steel Slag Bituminous Road Section LHS (ii) Steel Slag Concrete Road Section RHS

Figure A.2: Cross-Section of Steel Slag Road Section on NH- 66 (Mumbai-Goa National Highway)

Photo A.3: Laying of DLC layer and Inauguration of NH- 66 (Mumbai-Goa National Highway) steel slag road section by Hon. Member Niti Aayog Dr. V.K.Saraswat

Photo A.4: Aerial view of Cement Concrete and Bituminous Steel Slag Road Section on NH 66 Dolvi Mumbai

ANNEXURE-3

CASE STUDY- 3

STEEL SLAG ROAD BRO PROJECT ARUNACHAL PRADESH

Border Road Organization, Arunank Division built a Steel Slag Road section on Joaram-Koloriang Road at Ziro valley in Arunachal Pradesh in Dec. 2022 under CSIR- Central Road Research Institute, technological guidance. Processed BOF steel slag aggregates were supplied by TATA Steel Jamshedpur plant for construction of these test section. Around 1200 MT processed BOF steel slag aggregates were transported via. a Railway rack from Jamshedpur to Itanagar and further from Itanagar to project site near ziro valley via road. Bituminous concrete layers of 40 mm thickness were constructed using processed BOF Steel Slag Aggregates.

Photo A.5: Glimpse of Steel Slag Road Section Built at Ziro, Arunachal Pradesh by BRO

ANNEXURE-4

CASE STUDY- 4

STEEL SLAG ROAD NH-33 RANCHI-JAMSHEDPUR-KOLKATA

Under CSIR-CRRI technological guidance Processed BOF Steel slag aggregates were successfully utilized in the construction of L.H.S carriageway of six lane National Highway of NH-33 Ranchi-Jamshedpur-Kolkata section in 2016. Processed BOF steel slag aggregates were developed at TATA Steel Jamshedpur plant under CRRI technical guidance through accelerated weathering technique by carrying out alternate wetting and drying of BOF slag aggregates. These aggregates were further utilized as 100% substitute of natural aggregates in base course and sub-base course from chainage 258.000 to 258.500 of Jamshedpur to Mahulia section of NH-33 under CRRI technological supervision.

Infield evaluation of WMM and GSB layers were carried out by CSIR-CRRI team to determine the field density, in-situ permeability, material characteristic of base course and sub-base course layers.

Photo A.6: BOF Steel Slag Aggregates in GSB and WMM layers of NH 33 on natural soil embankment

Photo A.7: WMM layers with steel slag aggregates on NH- 33 after prime coat

Photo A.8: Team CSIR-CRRI at NH-33, Jharkhand after completion of road section

ANNEXURE-5

BRIEF OF CENTRE FOR RESEARCH ON STEEL SLAG

CSIR-CRRI with the financial support from Ministry of Steel, Govt. of India has established a state of art Centre for Research on Steel Slag in the year 2021 at CSIR-CRRI campus Delhi-Mathura Road, New-Delhi. This center is equipped with various steel slag characterization facility to carry out applied research for utilization of steel slag for various infrastructure application. Center is also equipped with the facility for infield structural evaluation of steel slag road using Heavy Weight Deflectometer and axle load spectrum using axle weight pad.

Photo A.9: Visit of Centre for Research on Steel Slag by Secretary, Ministry of Steel Shri Nagendra Nath Sinha, IAS

Photo A.10: Structural evaluation using Heavy Weight Deflectometer

CSIR CRRI

Azadi Ka Amrit Mahotsav

सत्यमेव जयते
Ministry of Steel
Government of India

STEEL SLAG ROAD TECHNOLOGY FOR SUSTAINABLE GREEN ROADS

WASTE TO WEALTH

Swachh Bharat Unnat Bharat

Steel Slag Road Technology is developed by CSIR-Central Road Research Institute New-Delhi to facilitate utilization of waste steel slag as substitute of natural aggregates in road construction. On the directives of Niti Aayog under the major R&D project sponsored by Ministry of Steel along with four major steel industries namely Arcelor Mittal Nippon Steel India, TATA Steel, Rashtriya Ispat Nigam Limited and JSW Steel, CSIR-Central Road Research Institute has developed customized steel slag valorization technologies to convert raw steel slag as Processed Steel Slag Aggregates" for road making. Processed steel slag aggregates can be utilized as 100% substitute of natural aggregates for bituminous and cement concrete steel slag road.

MAJOR STEEL SLAG ROAD PROJECTS ACROSS INDIA

SURAT, GUJARAT

SURAT, GUJARAT

BRO, ARUNACHAL PRADESH

NH - 33, JHARKHAND

NH - 66, MAHARASHTRA

NH - 66, MAHARASHTRA

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