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Converting Granulated Blast Furnace Slag into Fine Aggregate

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Abstract

With restrictions on indiscriminate dredging of river sand and stone crushing there has been a growing need in civil fraternity for identification of alternative fine aggregates. One promising alternative has been granulated slags generated in steel plants, but were limited to partial replacements due to property variations. Most of this slag is presently dumped. Granulated blast furnace slag (GBS) is physically similar to sand but has low density and has strength issues when used in concrete. In the present work a new processing technique has been developed to convert this slag into fine aggregate to be used as 100 % replacement to river sand, for construction purpose. This multiple stage processing involves change in structure and shape of the slag granules. Strength, durability and workability of the concrete casted with processed granulated blast furnace slag (PGBS) were found to meet the standard requirements of the cube tests. This innovative processed granulated blast furnace slag or slag sand is an economically viable and environmentally acceptable alternative material for replacing river sand having tremendous economic impact, conservation of natural resources and gainful re-cycling of process by-products. This slag sand is now extensively utilized and marketed by JSW Steel Vijayanagar works, India.

Keywords: granulation, concrete, fine aggregate, compressive strength,

INTRODUCTION

Concrete is one of the most consumed material in volumes and India being a developing country will require concrete in huge proportions. Approximately three-fourths of the volume of concrete is occupied by coarse and fine aggregates. Coarse aggregates are presently sourced from breaking large rocks and mountains which has long term environmental impacts. Fine aggregate or sand is mined from river bed which also is getting depleted and exhausted, and its excessive mining has led to the ecological imbalance. In India the demand for aggregates is continuously increasing. As per a recent estimate, India consumed 3330 MT of total aggregates (coarse and fine) in 2015 and will require 5075 MT of aggregates by 2020 [1]. With restrictions on mining of river sand and stone crushing, there has been a growing need in civil engineering fraternity for identification of alternative aggregates. In order to mitigate environmental impact, alternative materials to be used as fine aggregates are being extensively investigated all over the world [2-7]. Slag has been one of the most sought alternative aggregate material due to its similarity with aggregates and quantity generated by steel industries fits well into the demand supply gap. Until recently, slags were not regularly utilized in civil construction due to the ease of availability of natural materials, lack of awareness of its benefits, non-availability of application guidelines and limited slag processing techniques. Further, availability of slags only in areas close to steel plants, logistic problems of transportation and most importantly restrictions or non-availability of standards on usage of non-natural aggregates in construction have greatly impaired the use of slag into construction industry. With ecological concerns and environmental restrictions, availability of natural aggregates specifically river sand is greatly reduced and most of the developed countries have amended their aggregate standards to allow alternative or artificial aggregates such as slag in roads and construction [8-10]. Steelmakers have now started adopting modern slag processing techniques to convert slag as a product to meet the standards for construction requirements. Present development is a significant move towards protection of environment by introducing processed granulated blast furnace slag as an eco-friendly alternative to river sand. This initiative is first of its kind in the country.

GRANULATED BLAST FURNACE SLAG (GBS)

Blast furnace is an iron making unit which converts iron ore into molten iron through reduction reactions, in presence of coke and fluxes. In addition to molten iron, the furnace generates slags in the range of 250 to 500 kg per tonne of hot metal. "Slag" is a non-metallic product, consisting of glass containing silicates and alumino silicates of lime and is a byproduct of the conversion processes. On average, it contains about 0.5–0.8 % FeO, 32–42% CaO, 35–40% SiO2, 8–9% MgO, 10–19% Al_2O_3, 0.3–1.0% MnO and 0.7–1.5%S in weight. Granulated blast furnace slag is obtained by rapidly chilling (quenching) the molten slag at about 1,500 ^{o}C from the furnace by means of water and air. During this process of quenching, the molten slag undergoes accelerated cooling under controlled water flow condition and gets converted into glassy sand with 97 % of the solid granulated slag particles less than 4 mm as shown in Figure 1. Granulated BF slag is regularly used by cement industry for making portland slag cement; however conversion of this slag into fine aggregate and use as replacement of river sand is an innovative and novel approach to recycle slags.

Fig 1: BF Slag Granulation

PROBLEM

Granulated blast furnace slags are available with steel industry for decades but were never accepted as a fine aggregate in construction activities till this developmental work. Several test have been carried out which confirms that granulated blast furnace slag is inert, non-toxic, free from traditional impurities (i.e. organic impurities, shells, clay) and is chemically similar to an aggregate. Though it look alike sand, granulated blast furnace slag (GBS) does not meet the physical property requirement of the aggregate specifications and when used in civil applications has resulted in lower strengths. There has been numerous published works on utilization of BF slag sand as replacement of river sand under various conditions and varying proportions in mortar and concrete. Most of the papers [11-14] recommend the usage of granulated BF slag as replacement of river sand in the range of 50 - 75 %. This difference is due to the variation in the quality of BF slag sand being used from different sources. Here, it is pertinent to mention that the property requirement in granulated slags for use in cement and as aggregate is different. Slags to be used for cement making requires high glassy phase (>90%) whereas slags to be used as fine aggregate must have sufficient density (> 1400 kg/m^3) or specific gravity (> 2.5). This standard property is required to meet the weight requirement in cubic meter of concrete. Most of the studies used the granulated slag with the density range of 950-1100 kg/m^3 and this can be seen as the primary reason for reduction in strength with increasing proportions. Present work focussed on identifying the reasons for its reduced strengths and developing a processing technology for converting GBS into acceptable fine aggregate. A major drawback identified with the use of GBS in construction is the lesser bulk density (1000 -1100 kg/m3) in comparison to the of river sand (1300-1600 kg/m^3) which results in lower strength of concrete. Higher water absorption and lower specific gravity also contributed to its lower properties. Comparison of GBS properties with river sand is shown in Table 1. Microscopy studies showed that lower density in slags is due to its vesicular structure with micro pores present in the slag grains. The porous structure of GBS grains is shown in Figure 2.

Size distribution showed that the particles are mostly in coarse zones of standard size distribution and lack finer component. When used in concrete it lower down the compaction and reduces the strength. The coarser GBS particles have irregular shape and appear porous with sharp edges, whereas the finer GBS particles have needle or flaky shape with sharp edges. The glossy needle like particles renders the GBS difficult to handle with bare hands. Hence, if the GBS has to be used as fine aggregate as a replacement of river sand, its physical properties especially density, size distribution and shape must be modified. Various tests conducted under this study have confirmed that GBS can be used as 100% replacement of natural sand in concrete mix design if slag density can be increased to greater than 1400 kg/m3.

Table 1: Comparison of Physical Properties

Properties	River Sand	GBS
Size	IS 383 - Zone II (Fine)	IS 383 - Zone I (Coarse)
Density, Kg/m^3	1300 - 1600	1000-1100
Sp Gravity	2.6 - 2.8	2.3 – 2.5
Water Absorption, %	1 – 3	4 - 6

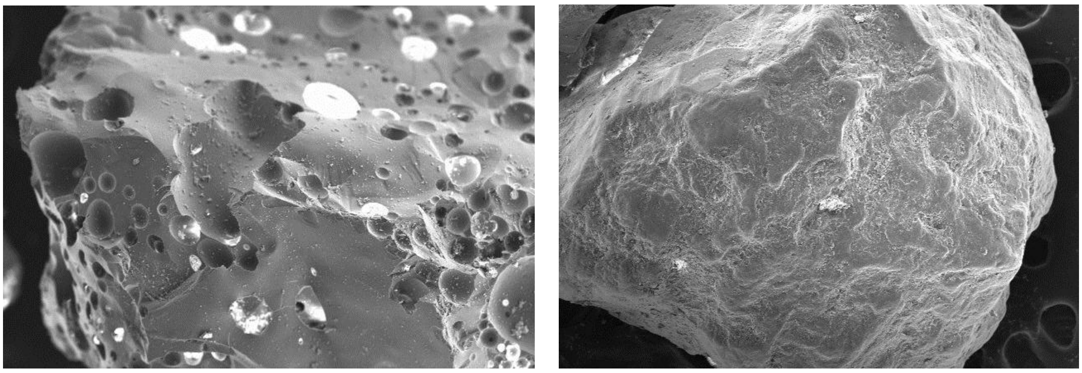

Fig 2: Comparison of particle morphology (a) River sand (b) GBS

PROCESSING

Conversion of GBS into a fine aggregate requires improvement structure and shape. The developed conversion process involves improving the physical properties in two stages.

- **Stage 1: Altering granulation parameters**

Slag Granulation is primarily affected by water temperature, water pressure and water flow rate. When the material solidifies under slow cooling conditions, escaping gases leave behind micro pores in the cooled mass. When formed under controlled rapid cooling, the slag tends to be hard and dense, making it suitable for use in all concrete applications. It was conceptualized that density and specific gravity of granulated slags can be increased by optimizing granulation parameters such as water temperature and flow rate to produce slag sand similar to river sand.

Based on this concept, several trials were conducted at blast furnace slag granulation plant, with varying water temperature and flow rates. The granulated slag samples were collected and analyzed for specific gravity, bulk density and structure through microscopy. It was found that reducing the jet water temperature reduced the porosity in the slag granules. The highly porous structure of earlier granulation slag has improved to much denser structure resulting in improved density. Figure 3 shows the effect of slag granulation water temperature on density. It was found that under optimum conditions of granulation parameters, the bulk density of the slag can be increased to > 1350 kg/m^3 as more compact structure can be developed in slag granules. Micro-graphs of the low temperature water spray granulated material shows lower porosity contributing to the increased density as shown in Figure 4. It was found that, to achieve the best result the jet water temperature has to be less than 50 ^oC and minimum water flow rate to be kept at 2500 m^3/hr. Accordingly the process parameters were changed to meet the optimized conditions. However, the shape and size distribution did not change much and the issue of needle or flaky shape particles still existed and required further modifications.

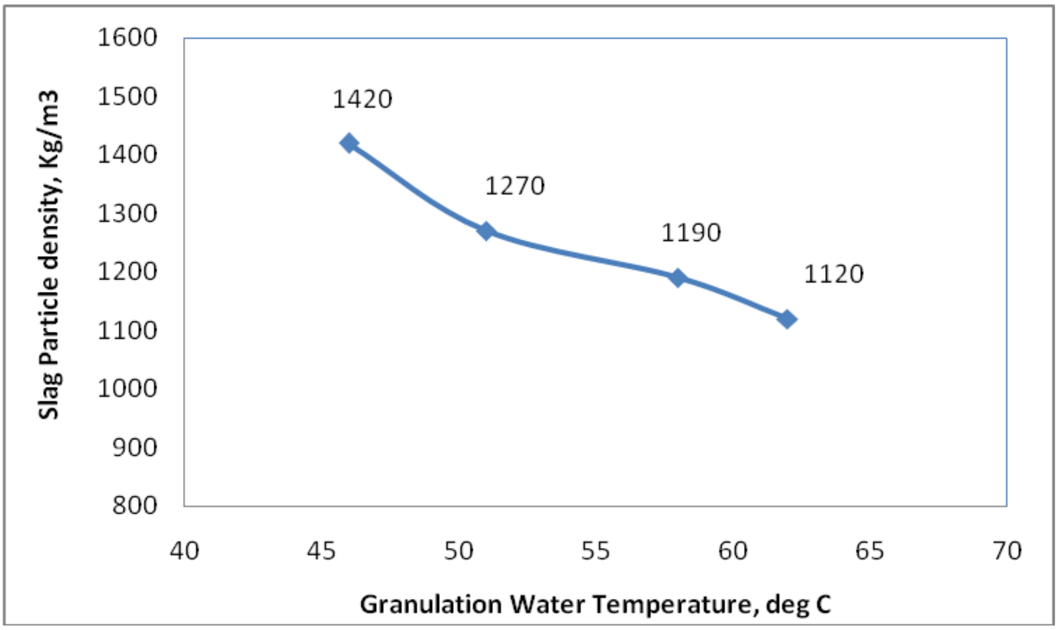

Fig 3: Effect of granulation water temperature on slag density

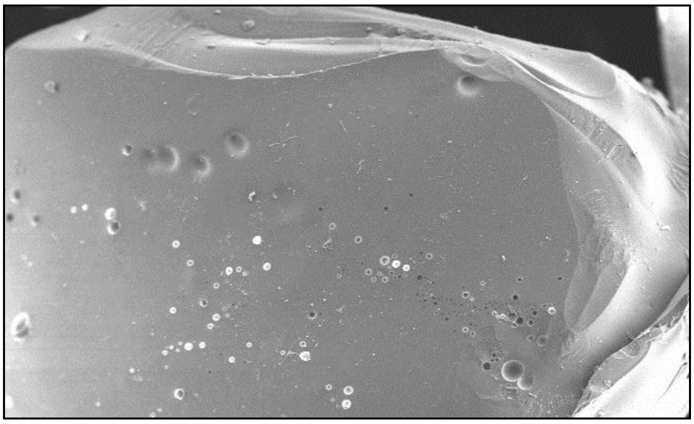

Fig 4: Structure of Low temperature water cooled slag

- **Stage 2: Shaping and Screening**

The second stage of processing was to address the needle or flaky shape of the particles by subjecting it to customized shaping and screening process. The purpose was to increase the finer portion of material (<300 microns) and to convert individual particles into rounded shape without breaking grains. Increase in the finer fraction would have also helped in increasing the bulk density. It was conceptualized that the slag particles should be subjected to abrasion process and not grinding to meet the shape and size requirement. As no customized equipment was available for abrasion process, it was decided to tune a vertical shaft impactor for achieving the desired function. Normally, a vertical shaft impactor is used for crushing stones. In a shaft impactor, feed material drops through the feed tube onto the impeller table or enclosed rotor which, through centrifugal force, throws the material against stationary anvils made up of composite metal alloys. When the rock particles impact the anvils, it shatters along natural stress lines, creating a uniform cubical product. This method of crushing is simple and economical to operate. A pilot scale vertical shaft impactor was brought and modified for studying the feasibility of achieving an abrasion function for slag particles. A simple design of shaft impactor is shown in Figure 5. In an impactor, the particle projectile velocity and impact force with which it hits the anvils decides whether the particle will get shaped, crushed or ground. Higher speeds results in pulverizing and grinding as shown in Figure 6. Hence the size and shape of the processed slag particle generated are controlled by feed rate and rotor speed. It was found that by manipulating the rotor speeds the feed material can be subjected to only shaping. Series of experiments were conducted by varying these variables and an optimized range of feed rate and rotor speed were established where the slag particles does not break and only change the shape. These parameters require continuous fine tuning based on the input mean average size particle. The impactor processed slag granules were of rounded shape but the size distribution required some alteration. Hence these shaped particles were subjected to screening to get the desired size range fitting to the standard. After the second stage of processing, the bulk density of the slag has further increased to 1500 kg/m^3 and is close to the value of natural river sand.

Water absorption reduced from 8% to < 3% and no needle shaped particles left out in the final processed material.

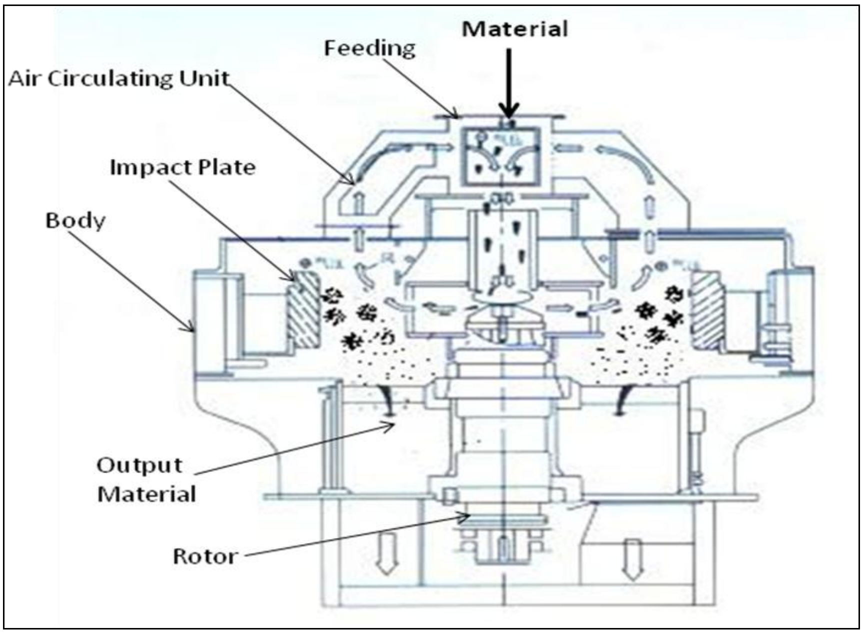

Fig 5: Vertical Shaft Impactor

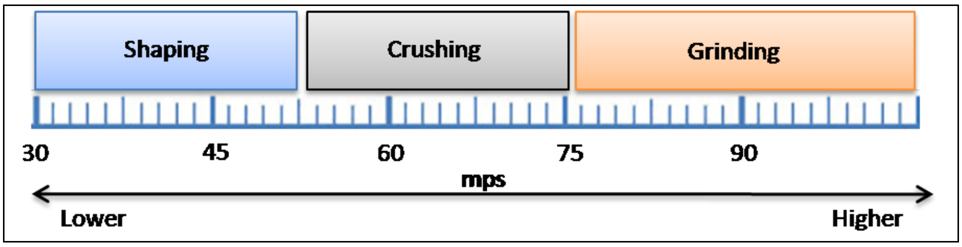

Fig 6: Effect of rotor velocity on particles in Vertical Shaft Impactor

TESTS AND RESULTS

The physical characteristics of slag samples have greatly improved after the processing. The particles shape has improved. The particles develop blunter edges as compared to the needle or flaky shape with sharp edges in GBS. The processed granulated blast furnace slag (PGBS) was similar to the true river sand. Properties of GBS, PGBS and river sand are compared in Table 2. The shapes of the natural river sand and PGBS particles resemble closely. Comparison of particles of river sand, GBS and PGBS is shown in Figure 7. Size distribution of the processed granulated slag was also similar to river sand. PGBS matched the required physical properties of fine aggregate to be used in concrete. Size distribution of PGBS is shown in Figure 8. In addition to properties, the key advantage of slag sand over river sand is absence of impurities like clay and silt.

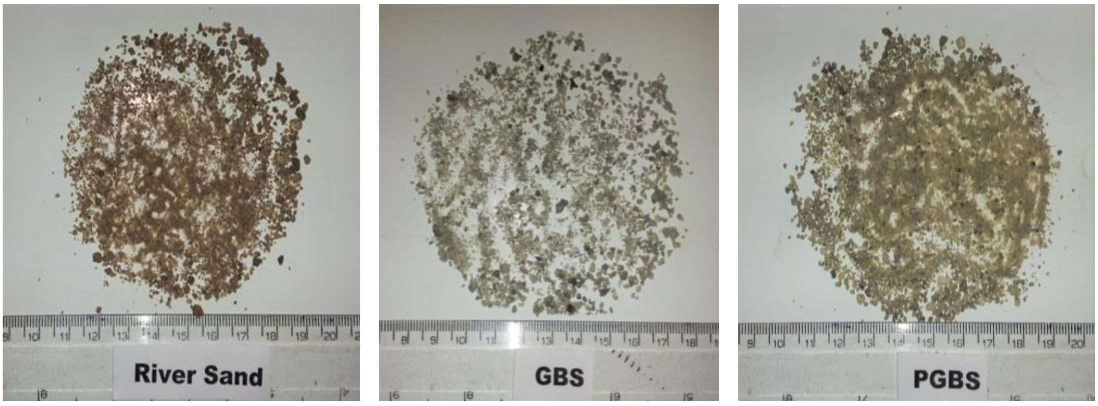

Fig 7: Particles of river sand, GBS and PGBS

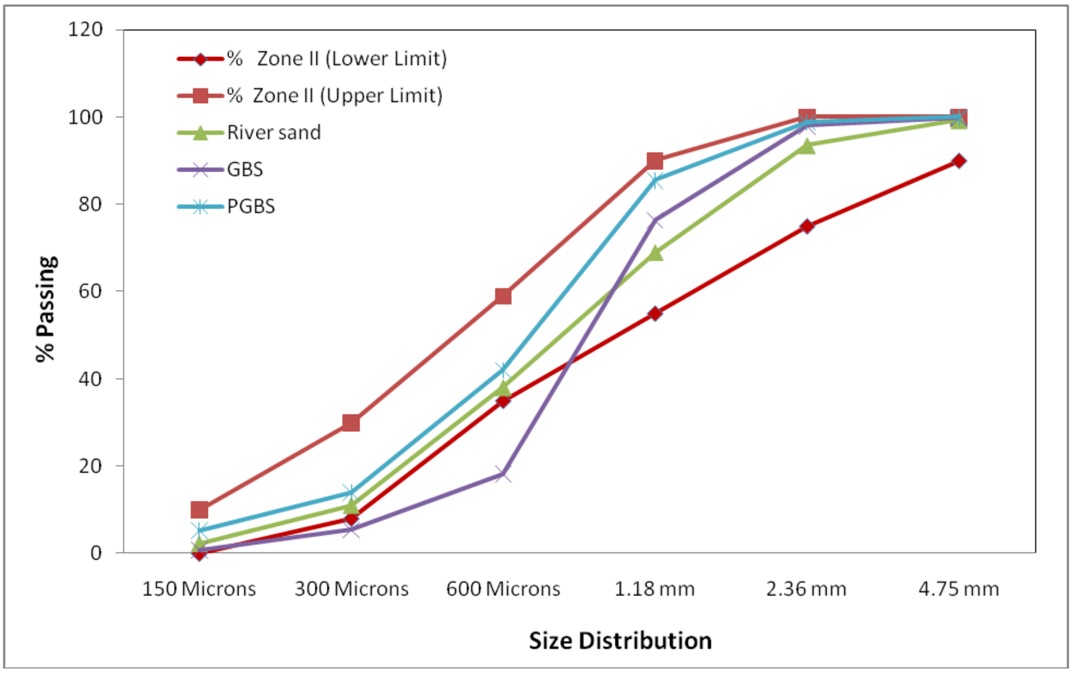

Fig 8: Size distribution curves of the GBS, PGBS and River sand

Table 2: Properties of GBS, PGBS and river sand

Properties	**River Sand**	**GBS**	**PGBS**
Size	IS 383 - Zone II (Fine)	IS 383 - Zone I (Coarse)	IS 383 - Zone II
Density, kg/m^3	1300 - 1600	1000-1100	1500
Sp Gravity	2.6 - 2.8	2.3	2.65
Water Absorption, %	1 – 3	4 -6	<3

Fig 9: Concrete cubes made using river sand, GBS and PGBS

Table 3: Comparison of cube strengths in M-40 grade concrete

Fine Aggregate	7th day Strength	28th day Strength
100% Natural Sand	38-42	48-52
100% GBS	36.5	45.5
100% PGBS	42.9	53.3
50% PGBS + 50% NS	39	52
50% PGBS + 50% M - Sand	40.8	52.3
50% PGBS + 50% Crusher	30.9	49.7

PGBS was then experimented for mortar and concrete cube testing, to check its strength when used with cement. The prepared concrete cubes are shown in Figure 9. The flow characteristics clearly indicate that the mortars with PGBS are equally good or marginally better than the mortars with river sand. The compressive strength of mortars using PGBS is much higher than the strength of mortar with river sand. Flexural bond strength of masonry using mortars having PGBS as aggregate is higher as compared to the masonry flexural bond strength with mortar using river sand. It is possible to achieve good workability for the concrete using PGBS as fine aggregate. The results clearly show that with PGBS as fine aggregate it is possible to arrive at mix proportion which yields desirable strength and slump, and meet the IS 456 requirements. The slightly angular shape of some slag particles increases the amount of surface area for bonding with cement paste and reduces the high internal stress concentrations leading to higher strength values. The bond strength between the rebar and concrete with river sand and PGBS as fine aggregate is found in similar range. Tests conducted at JSW Steel have shown that PGBS can be used 100 % individually and also in combination with Natural sand, Crusher dust and M-sand. The strength values are shown in Table 3.

The controlled granulation and impactor processed slag finally matched the specifications of the fine aggregate standard. This innovative processing methodology developed for blast furnace slag has converted a waste into a commercial product specially when availability of river sand is a serious concern and its prices are going up. Use of PGBS as fine aggregate in civil construction is a landmark development for steel and civil industry. As the civil fraternity resembles the fine aggregate with the word “sand” or “river sand”, a new terminology is coined as “SLAG SAND” for its easy identification and commercial advantage.

Tramp element studies proved that slags contain different types of heavy metals in very low concentrations and are well below the environmental norms and hence the newly developed slag sand does not have any environmental hazards and can be applied safely in aquatic environment, such as rivers, lakes or streams without impacting water quality or aquatic life. The use of slag as aggregate reduces the need for virgin material, energy and polluting emissions generated during the mining, processing and transportation of that material. This will also help in reducing the huge slag pile-ups by steel industries around their manufacturing units. Availability of a suitable alternative aggregate will help in controlling illegal and rampant mining of natural resources which causes disastrous impact on environment and economy.

The pilot scale study was expanded to a full scale plant by setting up an 800T/day Slag Sand preparation unit at JSW Vijayanagar Works as shown in Figure 10. The plant was designed to perform the shaping and screening of GBS. JSW Steel started dispatching slag sand to various states of Karnataka, Tamilnadu, Kerala and Andhra Pradesh in India.

Fig 10: Slag Sand preparation unit at JSW Steel Vijayanagar Works

The cost of the slag sand is much lower than the river sand within 300-400 kms of its production. Availability of low cost aggregate also help the local community in reducing their construction costs. This environmental friendly product has consistent quality and will be available throughout the year. This also negates the problem of non-availability of river sand during rainy season. This slag sand also has wide range of applications from plain concrete to reinforced concrete and can be used in roads, highways, paver blocks, bricks, mortar, plastering and masonry of building construction. JSW Steel is extensively utilizing the granulated slag in construction works as complete replacement of fine aggregate and in combination with crushed sand stone.

Most of the concrete roads are made using mix of crusher dust and granulated slag or granulated slag alone as replacement of fine aggregate. Use of slag sand at JSW Vijayanagar works in road, foundations is shown in Figure 11. JSW Steel is also utilizing slag in making paver blocks and concrete blocks.

Fig 11: Usage of granulated BF slag and crusher dust at JSW Vijayanagar works

BENEFITS OVER OTHER ALTERNATIVES

River sand and crushed rock are the two competitive alternatives to slag sand. The most commonly used aggregate is river sand collected from river bed but presently has availability and quality issues. Key advantage of slag sand over river sand is that, it does not contain organic matter, clay, silt and shells as shown in Table 4. Also, as the slag is produced at about 1,500 ^oC all compounds become inert and is safe to use. The other competitive alternative in India particularly is crushed rock (M-sand), the material generated from stone crushing. However due to environmental concerns, availability and strength requirements, their usage have been limited. It is also well known that M-sand or crushed rock can only mitigate the problem temporarily. Some lesser known alternatives used in civil construction include crushed glass, fly ash aggregate, bricks, roof tiles, pottery, burnt ash of garbage and sewage sludge, chopped plastics, mud etc utilized as alternative coarse and fine aggregates. However most of them have been limited to laboratories or demonstration level. Some of the feasible and economical solutions that have emerged in recent years are to reuse the industrial process wastes through recycling or reprocessing. Still, the alternative aggregates were not regularly utilized in civil engineering constructions due to easy availability of natural materials, lack of awareness of its benefits, non-availability of guidelines, limited processing techniques, near availability etc, but most importantly, due to the restriction on usage of non-natural aggregates in the standards. The level of alternative aggregate substitution which is achievable also depends upon the properties of the aggregate, its availability in the market, the performance criteria of the mix, the whole-of-life sustainability of the product and the economic viability of its inclusion. Additionally, the quality and availability of large quantities of alternative aggregates is still an issue. Among the various alternatives popular in market, the material which matches close to meet the quantity demand of the aggregates is slag sand. These materials can be made available in large quantities in India with total generation of 25 MTPA by all steel industries. Slag sand now have been experimented on large scale for a long time, have established durability studies, do not have any environmental and safety issues and are consistent in quality.

Table 4: Comparison of Impurities

	River Sand	PGBS
Marine Products	2 - 4%	Nil
Oversized Materials	6 - 10%	Nil
Clay & Silt	5 - 20%	Nil

JSW steel has become the first steel plant in the country to market and sell processed granulated slag or Slag Sand as replacement of river sand. Presently it has commissioned slag processing plant of 800T/day capacity and is in the process of expanding it to 5000T/day. The sale of slag sand is continuously increasing and is presently well accepted in civil construction.

CONCLUSIONS

In the present work a two stage processing technique has been developed for converting granulated blast furnace slag into fine aggregate to be used as an eco-friendly alternative to 100 % replacement of river sand in construction. The processing converts the low density and angular shaped slags particles to high density sand meeting the specifications. The performance of concrete samples prepared replacing natural sand by processed granulated blast furnace slag indicated that it could be gainfully utilized up to 100 % as replacement of river sand as well as partial replacement with manufactured sand and river sand . Processed granulated blast furnace slag has been extensively utilized at JSW Vijayanagar works and is now also commercially marketed.

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