Non-organic solid wastes – potential resource for construction materials

B. V. Venkatarama Reddy[1,]*, H. Hemanth Kumar[2], S. N. Ullas[3] and K. Gourav[4]

[1]Department of Civil Engineering, [2]KSCST and [3]Centre for Sustainable Technologies, Indian Institute of Science, Bengaluru 560 012, India
[4]Department of Civil Engineering, National Institute of Engineering, Mysuru 570 008, India

Construction industry consumes natural resources in bulk quantities for various products such as bricks/blocks, mortar, concrete, etc. Indiscriminate exploitation of natural resources to meet the ever-expanding needs of the construction sector is posing serious environmental concerns and resulting in scarcity of natural raw materials. At the same time, a large volume of non-organic solid waste (NOSW) is being generated through various anthropogenic activities. It is challenging to find environmentally safe and economically viable solutions for handling such waste materials. This article discusses the construction industry scenario in India, some estimates of NOSW and strategies for their utilization. Few case studies of R&D work on the possibilities of utilizing NOSW for construction products are illustrated. In particular, the technical feasibility of utilizing construction and demolition (C&D) waste and iron ore tailings (IOT) as raw materials for construction products is highlighted. Experimental results presented here on the properties of mortar and concrete when C&D waste and IOT are used as an alternative to fine aggregate for replacing the scarce river sand are promising, showing immense potential for utilizing NOSW for the manufacture of construction products and materials.

Keywords: Aggregates, construction materials, iron ore tailings, solid waste.

CONSTRUCTION sector consumes maximum amount of natural resources and energy. Manufacturing of construction products requires raw materials and energy. Majority of the raw materials are mined from the earth. Natural resources are mined indiscriminately for construction purposes, causing environmental problems. Energy is expended for converting the raw materials into useful construction products. In addition, the construction materials and products are hauled over long distances spending fossil fuel energy. There are many instances where laws have been enforced to preserve precious natural resources and even ban mining of sand from the river beds.

Raw material extraction, manufacture of materials, transportation and construction cause environmental damage and greenhouse gas (GHG) emissions. Estimates show that more than 40% of the total energy and 30% of the material resources are consumed by the habitat and related infrastructure[1]. Ruuska and Hakkinen[2] estimate that better construction and use of buildings in the European Union would influence 42% of energy consumption and more than 50% of all extracted materials. There is an urgent need for minimizing the mining of raw materials and reducing energy consumption.

Annual per capita consumption of construction materials is estimated at 1.8 and 3.6 tonnes in India and the world respectively[3]. Aggregates constitute about 60% of the total materials consumed. For example, in India per capita annual consumption of aggregates is about 1.0 tonne in contrast to about 0.20 tonnes food grains consumption. Consumption of cement has grown by leaps and bounds since the last three decades. A tonne of cement requires 5–6 tonnes of aggregates. Meeting the demand for construction materials using only mined resources from the earth is unsustainable. Industrial and mining activities create large quantities of non-organic solid waste (NOSW) or by-products. For example, more than 400 million tonnes of NOSW is generated annually in India[4]; a large amount of NOSW has accumulated over several decades[5]. This article is focused on assessing the potential of NOSW for the manufacture of construction materials and presents the results of R&D work on utilizing the NOSW in the construction sector.

Construction materials

Construction materials are being consumed in unimaginable quantities. Mani and Venkatarama Reddy[3] compiled the amount of construction materials consumed in bulk quantities in India and the globe. Their data clearly indicate that aggregates constitute about 60% of the construction materials consumed. Major sources for the aggregates are stones, river and stream beds. Figure 1 displays demand for aggregates in the Indian context. Aggregates are used for the construction of buildings as well as roads and other infrastructure projects. Total demand for aggregates is projected[6] at slightly more than 5 billion tonnes. India is currently facing a severe shortage of aggregates. Mere crushing of existing rock resources to generate aggregates leads to serious ecological and environmental

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*For correspondence. (e-mail: venkat@civil.iisc.ernet.in) problems. Figure 2 compares the per capita food grains and cement consumption in India. The per capita food grain production remains nearly constant at about 0.2 tonnes, whereas per capita cement production is growing at an exponential rate since the last three decades.

Construction materials are manufactured from mined resources and hence they are extracted in an unsustainable fashion. In order to keep pace with the demand for new construction, it is inevitable to examine for renewable and recyclable alternative materials. In such a scenario, deriving construction products from NOSW can mitigate the environmental damage caused by the mining of natural resources for the manufacture of construction products.

Non-organic solid waste

Various industries, coal-based power plants and mining activities have generated and continue to generate considerable volume of by-products (NOSW). Accumulated NOSW poses serious environmental problems in terms of safe storage and disposal. These are not bio-degradable but generally stable materials and some of them can undergo leaching. NOSWs are basically by-products from industrial and mining activity. The types of solid wastes from the mining and industrial sectors are as follows:

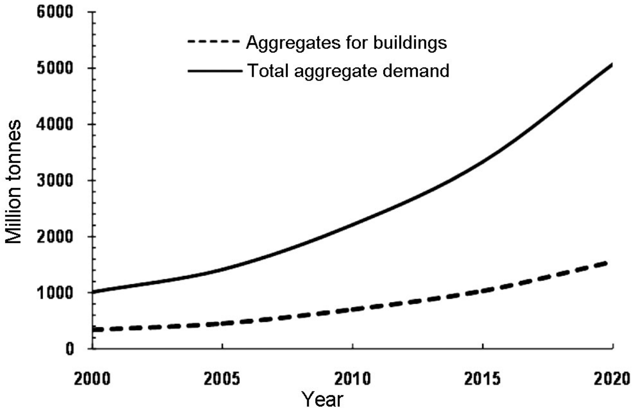

Figure 1. Demand for aggregates in India[6].

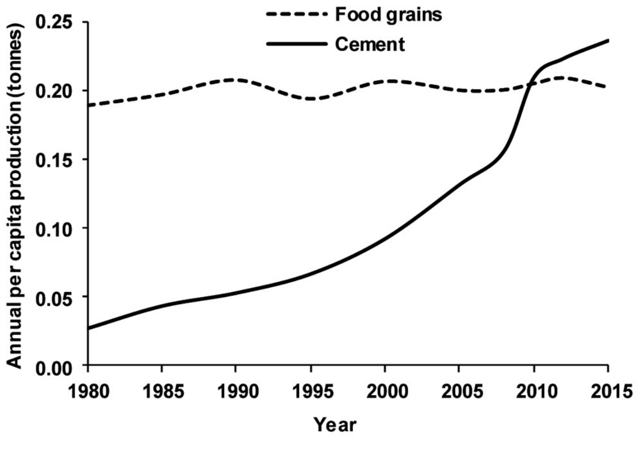

Figure 2. Food grains and cement production in India.

(i) Mining sector: Tailings from mines: iron ore, copper, manganese, bauxite, gold, etc.; Dust and debris: coal mines.

(ii) Industrial sector: Coal combustion residues: fly ash, bottom ash, pond ash. Agro industry residues: bagasse, rice husk, straw, groundnut shell, coconut husk, fibre, etc.; Fertilizer and chemical industries: lime sludge, phospho-gypsum; Metal industries: Slag, kiln dust, red-mud; Construction industry: construction and demolition wastes; Other industrial by-products: Stone dust, kiln dust, foundries.

Pappu *et al.*[4] estimated nearly a billion tonnes per annum of solid waste being generated in India including agro-waste. Coal combustion residues top the list of NOSWs. The current data indicate nearly 200 million tonnes of fly ash production in India. Yoshizawa *et al.*[7] estimated the global solid waste at 12 billion tonnes per annum, including municipal solid waste. They projected the annual solid waste generation at 25 billion tonnes by 2025. Every tonne of steel produced generates about 0.6 tonnes of slag. Steel industry alone generates nearly 40 million tonnes slag per annum in India. Construction and demolition (C&D) waste can be harvested easily and processed to produce building products. Large quantities of C&D waste are generated across the world. CRDA[8] estimated that 325 million tonnes of C&D waste is generated annually in USA. There are limited studies in assessing the C&D waste generated in India. Based on the studies of Venkatarama Reddy and Hemanth Kumar[9] for Bengaluru city (India), it can be projected that nearly 25–30 million tonnes of C&D waste is generated in India annually. A large amount of accumulated industrial and mine waste exists in India[4,5]. Considering the annual production of NOSW and the large quantities of existing accumulated wastes, there is considerable scope for exploiting these resources for the manufacture of construction products. This will also mitigate the shortage of mined raw materials being used for the production of construction materials. There are attempts to derive construction products from NOSW across the globe[4,5,10–38]. Details of some of these earlier attempts are highlighted below.

Fly ash is pozzolanic in nature and has been utilized for the production of cement, concrete, bricks/blocks, formation of embankments and road sub-bases[11,14]. Malhotra and Ramezanianpour[15] showed that the properties of concrete can be enhanced by the use of fly ash and give detailed notes on the performance of concrete having fly ash. Venkatarama Reddy and Chander[16] examined the properties of concrete blocks made from lean concrete mixes having fly ash replacing both cement and sand. It was found that the compressive strength of the blocks

Table 1. Summary of the literature on various types of NOSW and their application potential

Reference	Type of NOSW examined/reviewed	Applications
4	Fly ash, coal combustion residues, mine tailings, bauxite red mud, marble dust, phospho-gypsum, lime sludge	Blended cement, concrete, bricks, blocks, particle board, clay tiles
9, 20–35	C&D waste	Aggregates, bricks/blocks, concrete
10	Brick dust	Bricks/blocks
11–16	Fly ash	Bricks/blocks, blended cements, concrete
17	Phospho-gypsum	Concrete
18	Copper slag	Concrete, ceramic tiles
19	Blast furnace slag Red mud and fly ash	Blended cement, synthetic granite tiles
36–38	Iron ore tailings	Ceramic products, bricks, cement, glass, fertilizers
41, 42	Stone dust	Concrete
43	Copper slag	Concrete
44	Gold mine tailings	Back filling, geopolymerization

having fly ash increased by two- to three-fold compared to those without fly ash. The production and properties of compacted fly ash bricks and their masonry have been studied[12,13]. These studies recommended an optimum ratio of 35% fly ash and 65% sand for better strength and durability characteristics.

Ghafoori and Chang[17] studied the properties of concrete by replacing fine aggregates with phosphate mining waste. They showed that about 20% of natural fine aggregate in concrete can be replaced by phospho-gypsum. Gorai *et al.*[18] reviewed utilization of copper slag in making construction products (such as concrete, ceramic tiles, etc.). Sanjay Kumar *et al.*[19] studied the utilization of blast furnace slag, red mud and fly ash from metallurgical and allied industries for the manufacture of blended cement, synthetic granite tiles, etc.

Recycling of C&D waste is another area which has attracted wide attention for the manufacture of construction products. Several varieties of construction products have been explored using C&D wastes[4,8,9,20–33]. Ravindrarajah and Tam[34] studied the properties of concrete made from recycled crushed concrete fines. A mix design procedure for recycled aggregate concrete was developed by Bairagi *et al.*[35]. Das *et al.*[36] utilized iron ore tailings (IOT) as raw material in the production of ceramic tiles. Zhang *et al.*[37] recommended comprehensive utilization of IOT in China. Zhong-Lai *et al.*[38] prepared a cementitious material by compound thermal activation method using IOT as raw material. Table 1 summarizes earlier attempts on utilization of various types of NOSW for construction applications. The table provides type of NOSW waste and its possible application in the construction industry along with details of cited reference(s).

The literature reveals that there are several varieties of NOSW produced due to industrial and mining activities in considerable quantities in India and elsewhere. Also, large quantities of such waste have already been accumulated. There are attempts to derive construction products from NOSW across the globe. Many a times assessing the exact quantity of NOSW is a difficult proposition. Here we illustrate two case studies: (i) assessing the quantity of C&D waste in a metropolitan city and its utilization as fine aggregate and (ii) R&D on utilizing an accumulated mine waste as fine aggregate. In the first case study, a comprehensive methodology to assess the production of C&D waste in the metropolitan city was evolved, and experimental studies were carried out in utilizing the C&D waste as fine aggregate. In the second case study, IOT were explored for the partial replacement of conventional fine aggregate in masonry mortar and structural concrete.

Assessing the quantity of C&D waste

Bengaluru metropolitan city (i.e. Bruhat Bengaluru Mahanagara Palike (BBMP) region) encompasses approximately 800 sq. km area. The C&D waste generated in the BBMP region is conveniently dumped in some areas/spots. BBMP as such does not strictly regulate the dumping of C&D waste. Though BBMP has identified some dump sites for C&D waste, it usually gets dumped in many unauthorized areas. In order to assess the wastes generated and dumped in several places, the following methodology was designed and adopted.

(a) Identification of C&D waste dump sites through a survey of Google maps. (b) Physical verification of the sites identified through Google maps. (c) Identification of active dump sites. (d) Measurement of volume of accumulated C&D waste dumped. (e) Physically counting the number of trucks dumped in a day in the active dump sites. (f) Ascertaining the age distribution of C&D waste dump sites. (g) Estimation of C&D waste currently generated and verifying indirectly through the volume of accumulated waste and the age of the dump.

Figure 3 shows the Google map of the BBMP region. Figure 4 shows the map of C&D waste dump sites in the Bengaluru metropolitan region. There were a total of 26 sites identified through Google maps. These were physically verified and classified as minor, major and active dump sites. Table 2 provides details of these dump sites. The location, area and quantity of C&D waste in the dump sites are also given in the table. The area of spread of these dump sites varied in the range 1400 and 183,000 sq. m. The size and depth of these dumps was physically measured and the volumes estimated. Majority of the large C&D waste dumps are located in low-lying areas (Figure 5) such as tank beds and crates created by stone quarrying. Currently, there are five active dump sites as indicated in Figure 4. These sites were monitored by counting the number of trucks dumping C&D waste each day; it was found that on an average 80–120 truck loads are being dumped every day. The survey indicates that total volume of C&D waste accumulated over a period of 10 years amounts to about 3.0×10^6 m^3 (~5×10^6 tonnes) and fresh accumulation is about 0.5×10^6 m^3 (~0.75×10^6 tonnes) per annum. Considering the current population of the BBMP region, the C&D waste generated translates to about 0.1 tonne per capita per annum.

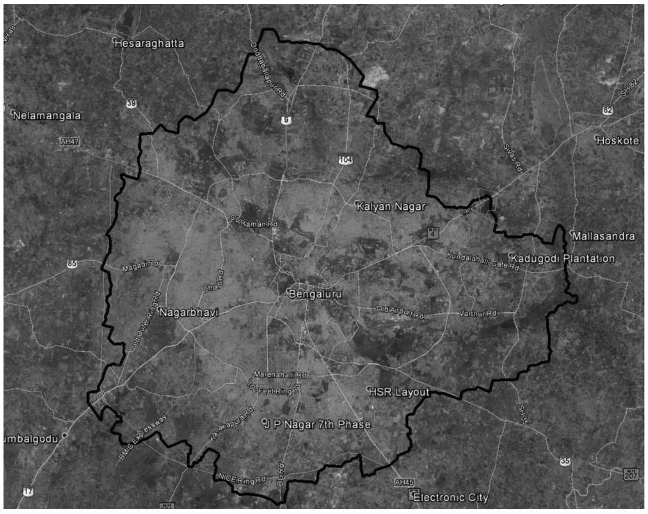

Figure 3. Google map of the BBMP region.

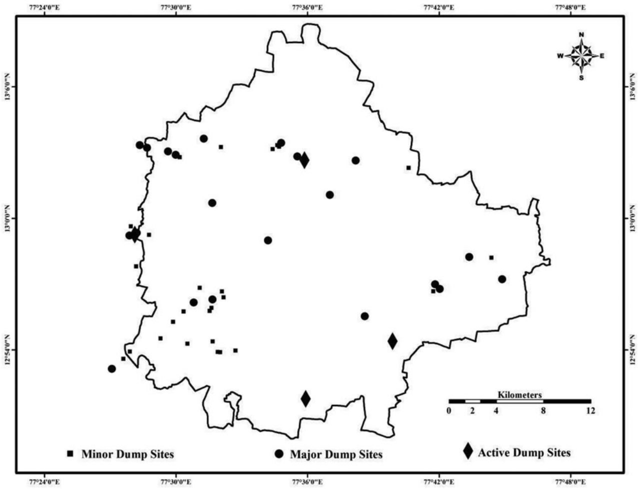

Figure 4. Construction and demolition (C&D) dump sites in BBMP region.

Testing the processed C&D waste for fine aggregates in mortar and concrete

Figure 6 shows the different types of C&D waste comprised of a mixture of broken bricks and stones, concrete

Table 2. Details of C&D waste dumps in the Bengaluru metropolitan region

Dump site location	Area (m^2)	Volume (m^3)
Hebbal, near bus depot	93,569	561,414
Hebbal flyover	3,690	18,450
TATA Nagar	19,121	19,121
Thanisandra	9,629	28,887
Venkteshpuram, Nagavara	23,427	23,427
Kengeri Hobli, RR Engg College	1,366	1,366
Near Prestige Ozone, White field	183,013	183,013
Pramodnagar, near PESIT	4,253	25,518
Opposite to Parle Factory	9,994	14,991
Shettihalli, Airforce compound	16,683	25,025
Nelamangala, Kenna Metal WIDIA	9,686	14,529
Opposite to Madhavara bus stop	6,695	10,043
Next to NICE road, Madhavara	9,778	9,778
Dodda Gollarahatti – A	3,126	9,378
Dodda Gollarahatti – B	9,173	9,173
Laggere flyover	17,904	268,560
Chikka Gollarahatti	10,972	43,888
Okalipuram, near Railway Bridge	4,393	35,144
Kundalahalli, White field	73,183	73,183
Near Marathalli flyover	55,024	275,120
Near Marathalli flyover	12,880	12,880
Haralur, near Koramangala	17,723	354,460
Near Agara lake, Koramangala	166,980	166,980
Hulimavu	64,400	257,600
Near Hulimavu lake	12,180	24,360
Hulimavu, near Nyayappanahalli	83,300	83,300
Total in major and active dump sites		2,557,298
Quantity in 26 minor dump sites		500,000
Total (m^3)		3,000,000

Figure 5. C&D waste major dumpsite (Hebbal, near bus depot) in Bengaluru.

Table 3. Physical characteristics of river sand and crushed C&D sand samples

	Type of sand				
Properties	LSC*	Crushed brick	Crushed mortar	Crushed masonry	River sand
Textural composition (% by weight)					
Coarse sand: (4.75–2.00 mm)	23.4	24.3	21.0	20.3	4.0
Medium sand: (2.00–0.425 mm)	38.8	40.8	51.9	38.9	74.2
Fine sand: (0.425–0.075 mm)	25.2	26.2	20.7	23.9	21.8
Fines fraction <0.075 mm	12.6	8.7	6.4	16.9	0.0
Fineness modulus	2.54	2.67	2.82	2.38	2.61
Specific gravity	2.48	2.66	2.59	2.60	2.62
pH	10.85	8.09	9.23	8.73	8.66

*Lime surkhi concrete.

Figure 6. Different types of C&D wastes.

pieces, mortar pieces, masonry pieces, lime surkhi concrete (LSC) pieces, broken tiles, soil, etc. To a large extent, C&D waste is free from plastics and other organic matter. The literature review reveals that concrete forms the major constituent material in C&D waste generated in many developed countries. Hence, majority of the earlier studies were biased towards utilizing cement-concrete-based C&D waste, mainly for aggregate production. However, in the present study, C&D waste generated was found to have higher volume of broken masonry and its constituents, and LSC than cement–concrete. This may be the case for C&D waste in other up-coming Indian cities, where older structures predominantly have brick masonry. The studies on exploring masonry-based C&D waste are scanty. Hence, four types of C&D waste (excluding cement–concrete, which has been widely examined by other researchers) were selected to examine their suitability as fine aggregate. LSC, mortar, bricks and masonry constitute the four types of demolition waste selected. Each of these was crushed to a fineness of less than 4.75 mm. Table 3 provides the textural composition and other physical characteristics of the C&D waste crushed sand samples as well as the natural river sand. C&D waste crushed sand contains some amount of fine particles (<0.075 mm) in the 6%–17% range. This is attributed to the presence of particles such as brick pieces, lime, etc. in the C&D waste. The fineness modulus of the different types of fine aggregates from C&D waste and river sand was in the 2.4–2.8 range. The pH of LSC and mortar crushed aggregate was more than that of the other three types of aggregates. This can be attributed to the fact that LSC and mortar aggregate contain residual lime.

The processed C&D waste was examined for its suitability as fine aggregate in mortar and concrete. Two types of mortar (M1 and M2 grade according to IS 1905 classification)[39] were examined for compressive strength. M1-grade mortar consists of 1 : 1 : 6 cement : lime : sand by volume, whereas M2-grade mortar consists of 1 : 6 cement : sand by volume. Workability and compressive strength of concrete using C&D waste crushed fine aggregate were examined by replacing the river sand from 0% to 100% in M20-grade concrete (20 MPa characteristic compressive strength).

Figure 7 shows a bar chart comparing 28-day strengths for the two types of mortars using different types of fine aggregates. Crushed fine aggregate from C&D waste yielded more strength for the two types of mortar compared with the strength corresponding to the mortars with river sand. Higher strength for the mortars with crushed C&D waste sand can be attributed to the presence of pozzolanic materials which react with lime resulting in additional strength.

Figure 8 shows a plot of compressive strength of concrete versus sand replacement with crushed C&D waste aggregate. The figure also shows the mean strength required to achieve a characteristic compressive strength of 20 MPa. Concrete strength decreases with the replacement of river sand by C&D waste sand. LSC crushed aggregate gives the lowest strength among the different types of aggregates examined. This can be attributed to high water : cement ratio to achieve the slump using LSC sand. Characteristic mean strength of 26.6 MPa can be achieved even with crushed C&D waste sand with higher water : cement ratio than specified in the IS 456 code[40]. Among the crushed C&D waste aggregates, fine aggregate from crushed mortar gives the highest strength for concrete.

The study has revealed several interesting features on fine aggregates from C&D waste. Nearly a million tonnes of C&D waste is produced annually in the Bengaluru metropolitan region, apart from the huge quantities of such accumulated waste. Demolition waste is nearly free from plastics and other organic matter.

Sand from crushed C&D waste can be used for masonry mortar and concrete. Compressive strength of concrete falls marginally when river sand is replaced by sand from C&D waste (like crushed mortar and crushed masonry). However, there is scope for exploring the characteristics of concrete using sand from a mixture of different types of C&D waste.

R&D on utilizing an accumulated mine waste as aggregate

Kuduremukh Iron Ore Company Ltd (KIOCL) is a Government of India enterprise established in the year 1976. For about three decades KIOCL mined and processed the iron-rich magnetite ore present in the Kuduremukh region of Karnataka, India. A 108 m depth earth dam was built to store IOT generated after processing the ore. Three decades of mining and processing the iron ore have accumulated 200 million tonnes of IOT, which is currently stored in the dam to a depth of 100 m, spread across an area of about 2 sq. km. The dam is located at 13°14′56″N and 75°13′30″E (Figures 9 and 10). This location is part of the Western Ghats of India.

The IOT samples were collected at 1.0 m depth from the surface across the storage area of the dam and designated as L1, L2, L3, L4, L5 and L6. Figure 11 shows the grain size distribution curves for IOT samples and river sand. The IOT samples were considerably finer than natural river sand. The average fineness modulus of IOT samples taken from six locations was 0.2, while it was 2.71 for natural river sand. The average sand, silt and clay size fractions were found to be about 69%, 28.5% and 2.5% respectively. The IOT samples were used in the experimental investigations. The following tests were carried out using IOT samples as fine aggregate in mortar and concrete. (i) Grain size distribution and physical properties of IOT samples; (ii) Compressive strength of masonry mortar using IOT as fine aggregate; (iii) Compressive strength of concrete using IOT as fine aggregate.

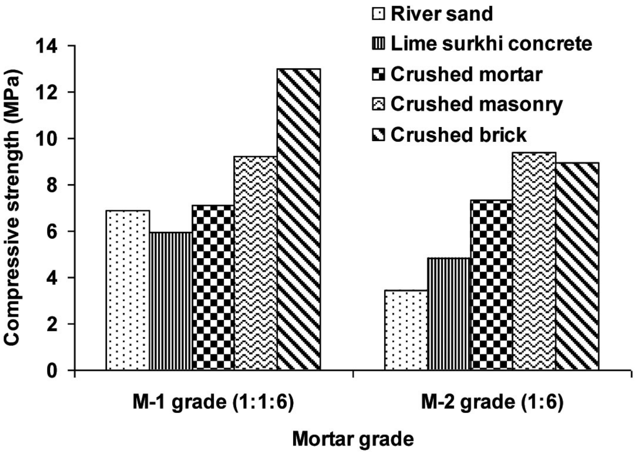

Figure 7. The 28-day compressive strength of mortars with different types of fine aggregates.

Three types of mortar (M1, M2 and H2 grade according to IS 1905 code)[39] were considered. The proportions of M1 and M2 have been discussed in the earlier sections. H2-grade mortar consists of 1 : 0.25 : 4 cement : lime : sand, by volume. River sand in the mortars was replaced by IOT ranging from 0% to 100%. Figure 12 shows the variation in mortar strength as IOT content is varied. The results show that the compressive strength of mortar peaks at 25%–50% sand replacement by IOT. Up to 75% of sand can be replaced by IOT without compromising on the compressive strength comparable to standard mortar compressive strength with 0% IOT.

Figure 13 shows the compressive strength of concrete with IOT content. Two types of concrete grades (M20 and M30 according to IS 456 code designation)[40] were examined. M20 grade corresponds to a characteristic compressive strength of 20 MPa, while M30 grade corresponds to 30 MPa characteristic compressive strength. The strength of the concrete was examined by replacing sand with IOT as fine aggregate in the range 0–100%. Figure 13 shows that the concrete compressive strength is maximum at an IOT content of 25%. However, the target mean strength for concrete can be achieved with 50% sand replacement by IOT. Figure 14 shows a building constructed with blocks, mortar and concrete containing IOT as fine aggregate. The major conclusions from the present study are highlighted below.

- The IOT samples are fine-grained compared to natural river sand. However, the standard codes of practice allow deviation in particle size distribution if the end result on performance of mortar or concrete is found satisfactory.
- The study shows that about 75% of natural river sand could be replaced with IOT to achieve majority of desirable mortar properties.
- It is possible to achieve strength and durability requirements similar to that of control concrete by replacing 50% sand with IOT.

The studies on the C&D waste and IOT show that there is a scope for utilizing such waste in construction. More detailed studies may be required, especially on concrete using IOT as fine aggregate.

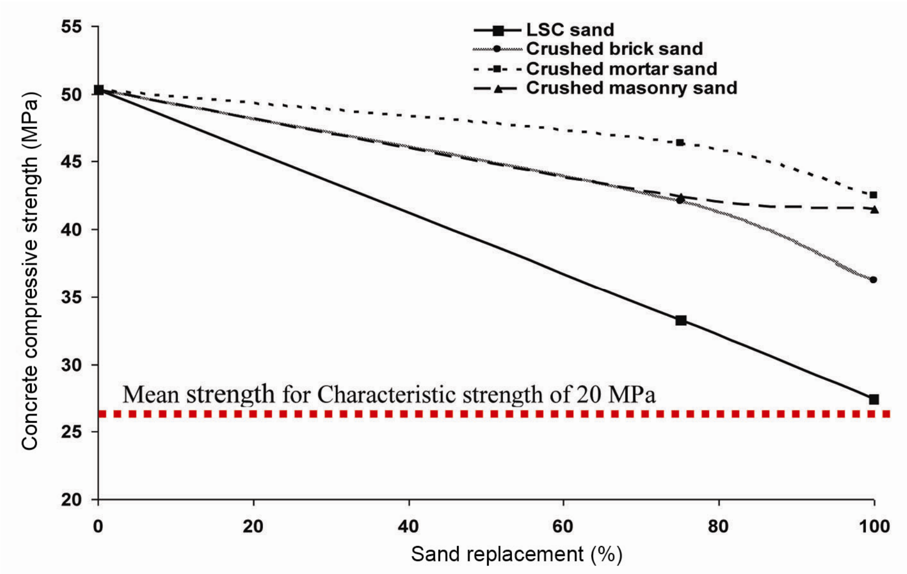

Figure 8. Strength versus sand replacement by C&D crushed sand for concrete.

Figure 9. Google map showing iron ore tailings stored in the Lakya dam.

Figure 10. Lakya dam (top view) showing storage of iron ore tailings.

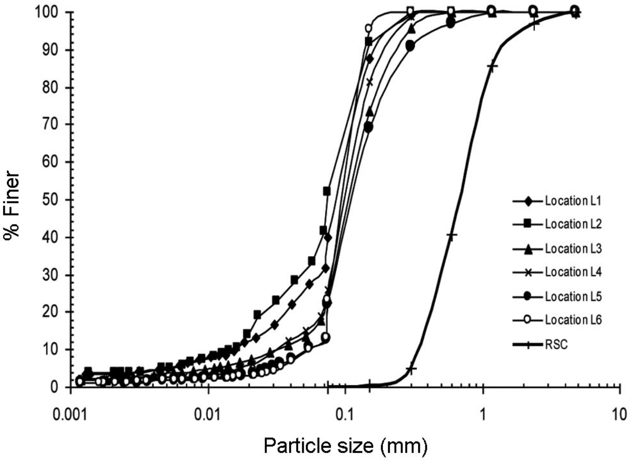

Figure 11. IOT samples and sand grain size curves.

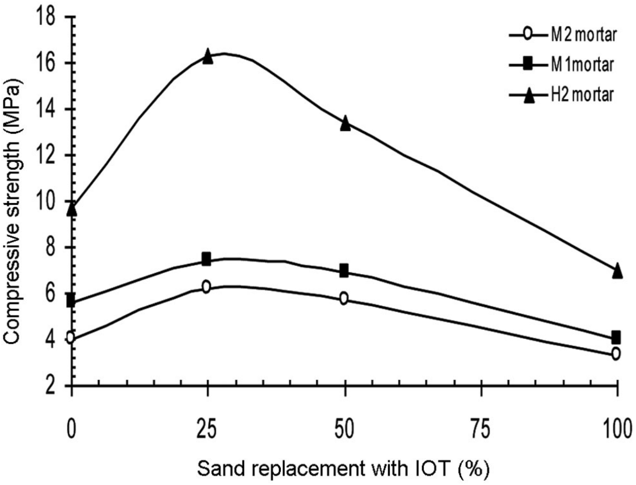

Figure 12. Mortar strength versus sand replacement with L5 IOT.

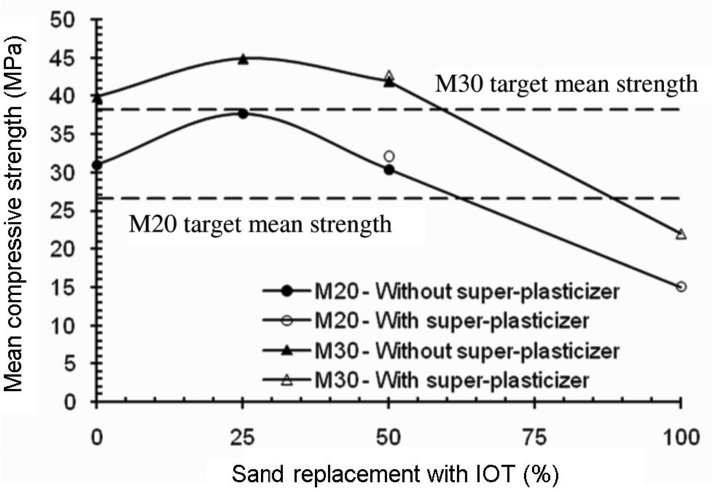

Figure 13. Strength versus iron ore tailings for M20 and M30 grade concrete.

Figure 14. Demonstration building using IOT as fine aggregate.

Concluding remarks

The problems related to mining of natural resources for the production of construction materials have been discussed here. It is imperative that there is an urgent need for exploring the alternative sources for raw materials to mitigate the problems of mining resources from the earth. Industrial and mining activity has generated and continues to generate large quantities of NOSW. There are several attempts to utilize solid waste for the production of construction materials. Recycling of NOSW into construction products will help solve the environmental problems associated with the storage of waste products and simultaneously mitigate the problems of mining the raw materials from the earth. Thus, there is immense potential for utilizing the NOSW for the manufacture of construction materials.

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