Waste-Derived Manufactured Aggregate For Concrete Permitted in IS: 383 – 2016

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Taking note of non-availability and difficulty in having coarse and fine aggregate for concrete from natural sources in some parts of the country and need of effective management of waste materials, BIS has recently permitted use of recycled concrete aggregate (RCA), iron and steel slag, copper slag and bottom ash. These have been called 'manufactured' aggregate in IS:383-2016. The decision is in line with results of copious R&D carried out in the country, some of which are described in the paper.

Introduction

Aggregates, coarse and fine, occupy nearly 75 per cent of volume of concrete. Next to water, concrete is the most widely used material the world over. One of the reasons for this wide acceptance is that the ingredients of concrete are either naturally occurring, or made from naturally occurring raw materials. Industrial waste materials also find increasing acceptance in making cement and concrete.

Most project specifications prescribe aggregate from natural sources. In particular, it is required that coarse aggregate shall consist of clean, hard, strong, dense, non-porous and durable pieces of crushed stone, crushed gravel, natural gravel or combination. Fine aggregate shall be natural sand, crushed stone, crushed gravel and combination, and Grading of Zone I, II and III are preferred.

Great challenges are being faced in obtaining quality aggregates from natural sources for concrete constructions [1]. In particular, there are restrictions on the use of river sand because of environmental and ecological concerns of erosion of soil in the river bed, change in the course of the river and stability of the banks, causing floods. This led BIS to permit alternatives in the recent revisions of IS: 383 in 2016. A summary of recommendations is extracted in Table 1.The decision was based on proposals emanating from copious indigenous research [2]. The relevant R&D is discussed in this paper.

Recycled Concrete Aggregate

Recycled concrete aggregate is obtained by processing construction and demolition (C&D) wastes [3]. Recent revision of IS: 383 recognise use of C&D wastes for obtaining aggregates as a step towards effective management and utilisation of this waste. This however, requires necessary processing and care to ensure their efficacy in their use in concrete. These aggregates may be of two types: Recycled Concrete Aggregate (RCA) derived from concrete rubbles after proper processing, and Recycled Aggregate (RA) made from C&D waste comprising concrete, brick, tiles etc. [3].

Recycled concrete aggregate (RCA) contain not only the original aggregate, but also hydrated cement paste. This paste reduces the specific gravity and increases the porosity compared to similar virgin aggregates. Higher porosity of RCA leads to a higher water absorption. Recycled aggregate will typically have higher absorption and lower specific gravity than natural aggregate [3].

The main influence of RCA is on the strength characteristics of concrete made with it, which is generally lower than that those made with virgin aggregate, the reason for the loss of strength is usually associated with [4].

The weaker interfacial transition zone (ITZ) between the aggregate phase and the mortar, due to the aggregate already having a coat of weak mortar attached on its surface, and this attached mortar raising the porosity of the resultant concrete.

In fact, all the properties of concrete dependant on the surface characteristics of coarse aggregate are affected. Such properties are: compressive and tensile strength, workability,

Table 1: Extent of Utilisation of Manufactured Aggregate (IS:383-2016)

S.No	Type	Extent of Utilisation, %		
		Plain Cement Concrete	RCC	Lean Concrete (≤ M15 Gr)
Coarse Aggregate	Iron slag	50	25	100
	Steel slag	25	Nil	100
	RCA	25	20 (≤ M25 Gr)	100
	RA	Nil	Nil	100
Fine Aggregate	Iron slag	860 790	38.22 35.11	36.66
	Steel slag	25	Nil	100
	Copper slag	40	35	50
	RCA	25	20 (≤ M25 Gr)	100
	Bottom Ash	nil	nil	25

elastic modulus, and durability characteristics like water absorption, sorptivity, drying shrinkage, abrasion resistance and chloride ion penetration [5].

R&D on Use as Coarse Aggregate

All the above-mentioned properties of concrete containing recycled concrete aggregate can be improved by proper processing of the RCA. Recent research on use of recycled concrete aggregate in M75 grade concrete, after due processing and improved mixing techniques have been published (4, 5). The effects of removal of adhered mortar are summarised below.

Materials used in this investigation were Portland pozzolana cement conforming to IS: 1489 – Part I, fine aggregate (river sand) and virgin coarse aggregate (10mm and 20mm sizes) conforming to IS: 383, Silica fume conforming to IS: 15388 and Superplasticiser (PCE based) conforming to IS: 9103. Water used was from municipal supply (IS: 456). The control concrete mix was of M75 grade having target 28-day strength of 82 MPa and 120 ± 10 mm slump. The mix proportions are in Table 2.

Table 2: Mix Proportions

Materials	Quantity, kg/cum
Cement (PPC)	500
Silica fume	35
Water	130
Fine aggregate	680
Coarse aggregate	1150
Superplasticiser	8 (1.6% bwoc)
w/b ratio	0.243

Varying amounts of coarse aggregate from natural sources were replaced by RCA in steps of 10 per cent, up to 100 per cent. Demolished concrete boulders (size ranging from 100 to 300 mm) from 10 years old 300 mm thick rigid pavement were collected. Selected boulders were made free from any contaminants. A crushing plant for producing crushed-rock aggregate, comprising primary jaw crushers and secondary cone crushers and screens, was used to produce coarse RCA in two size fractions, 20-10 mm and 10-5 mm (Figure 1).

Fig. 1: Unprocessed Recycled Aggregate

The recycled aggregate (RCA) from the crushing plant was further processed in a Los Angeles abrasion test machine by using steel balls and rotated a total number of 700 revolutions @ 33 rpm for each batch of total weight 10 kg (5 kg each for two sizes of 20-10 mm and 10-5 mm). Such processed material was discharged from the machine and washed manually with water properly, till the water after washing was clean. The washed material was air dried and stacked in the laboratory before use in the experimental programme (Figure 2). All the aggregates including processed RAC were used in saturated surface-dry condition.

Fig. 2: Processed RCA (after 500 rev)

Tests on hardened concrete were carried out for ages up to 180 days; results up to 28 days are discussed here. Till the age of testing, the specimens were moist-cured. Typical results of compressive, flexural and split tensile strength of concrete with different proportions of recycled concrete aggregate, which were subjected to 500 revolutions, are shown in Table 3 (5).

In so far as the effect of processing was concerned, it was observed that all the properties of concrete improved with the number of revolutions in LA machine, for any level of replacement by RCA. The workability and strength of concrete decreased as the proportion of RCA increased. Compared to reference concrete with virgin aggregate, 140 mm slump gradually decreased to 80 mm with 100 percent RCA; similarly, the 28-day compressive strength gradually decreased from 85.4 MPa to 62.3 MPa. In effect, it will mean that 60 MPa concrete with 80 mm slump was possible with 100 per cent processed RCA. However, the decrease in durability parameters (reported in Ref. 5) was more pronounced, which will restrict the proportion of replacement of virgin aggregate by processed RCA.

Use of Fine Fractions as Fine Aggregate

The fine fractions obtained during processing of concrete rubbles can be used as fine aggregate. Use of finer fractions (< 4.75 mm) of recycled concrete as part replacement of fine aggregate from natural sources was investigated. The results have been published recently [6]; as such, only salient findings are reported here.

Table 3: Concrete Strength Properties with Processed RCA(4)															
5 RCA, (500 rev.)	Compressive Strength(MPa)					Flexural Strength (MPa)					Split Tensile Strength (MPa)				
	7-day	28-day	56-day	90-day	180-day	7-day	28-day	56-day	90-day	180-day	7-day	28-day	56-day	90-day	180-day
0%	70.69	85.43	93.81	99.33	120.1	8.87	14.93	15.67	16.73	18.13	4.44	5.25	6.65	7.02	7.60
10%	65.71	81.92	89.69	95.18	115.6	8.07	13.60	14.60	15.40	16.86	4.09	4.94	6.58	6.67	7.46
20%	63.04	80.51	87.90	92.50	110.1	7.73	13.00	13.73	13.80	16.20	3.97	4.80	6.40	6.44	7.40
30%	59.41	78.34	85.68	90.01	108.8	7.46	12.5	12.93	13.20	15.86	3.90	4.73	6.31	6.37	7.34
40%	58.43	75.40	83.22	87.68	106.2	6.93	11.53	12.33	12.80	15.20	3.86	4.63	6.08	6.21	7.19
50%	55.52	73.23	82.01	84.41	102.0	6.66	11.26	12.20	12.53	14.80	3.80	4.60	6.04	6.11	6.95
60%	54.76	71.30	80.60	82.47	99.58	6.46	10.80	12.00	12.06	14.20	3.78	4.51	6.03	6.08	6.69
70%	52.23	68.79	79.30	80.36	94.25	6.07	10.13	11.40	11.80	13.73	3.68	4.39	5.93	5.98	6.51
80%	50.00	65.43	78.37	79.85	90.19	5.80	9.60	11.00	11.26	12.93	3.57	4.29	5.89	5.95	6.42
90%	47.96	63.03	75.41	76.84	88.95	5.53	9.00	10.13	11.00	12.26	3.46	4.13	5.51	5.93	6.35
100%	45.89	62.30	74.82	75.98	84.42	5.40	8.07	9.20	10.26	11.80	3.36	3.98	5.47	5.82	6.23

The < 4.75mm fraction obtained was brought into grading zone II conforming to IS 383-1970, by suitably mixing. Properties of fine aggregate from natural sources and recycled concrete are compared in Table 4. The quality of recycled aggregate is judged in terms of materials content, density and water absorption [3]. In many specifications, the limits of specific gravity (minimum) and water absorption (maximum) are 2.2 and 5 per cent (South Korea) or 2.2 and 7 per cent (Japan) respectively. If similar specifications are adopted in India, the present sample of recycled fine aggregate will satisfy the same.

Table 4: Properties of Fine Aggregate from RCA (6)			
S. No.	Material	Water Absorption	Specific Gravity
1	Natural Sand	0.21	2.6
2	RCA	6.2	2.41

Two control concrete mixes viz. M30, M40 grades were designed using virgin aggregates. Further mixes were obtained by replacing the fine aggregate fraction with RCA in steps of 10 percent, up to 50 percent. No other changes were made.

The target slump of 75 mm was reduced to 65 mm (M30 grade) and 59 mm in M40 grade, when 50 percent of natural sand was replaced by RCA. This lowering of workability can be offset by use of chemical admixtures and using the aggregate in saturated surface dry condition. Compressive strength of concrete of M30 and M40 grades were continuously decreasing with the increase in replacement percentages of natural sand by RCA. Results for M40 grade concrete are shown in Figure 3.

The compressive strength was lower by11.3 percent for M30 grade and 7.1 percent in case of M40 grade at 28 days, when 20 percent of natural sand was replaced by recycled aggregate [6].

Iron and Steel Slag

IS: 383-2016 allows use of Iron and steel slag as alternate coarse and fine aggregate. Iron slag (Blast Furnace slag) is obtained as by-product during manufacture of iron in blast furnace or basic oxygen furnace in integrated iron and steel plant. It can be air-cooled or granulated; the latter being light-weight, should be processed further to have bulk density > 1.3 kg/l for use in normal weight concrete. These must satisfy test for 'iron unsoundness' specified in the specification.

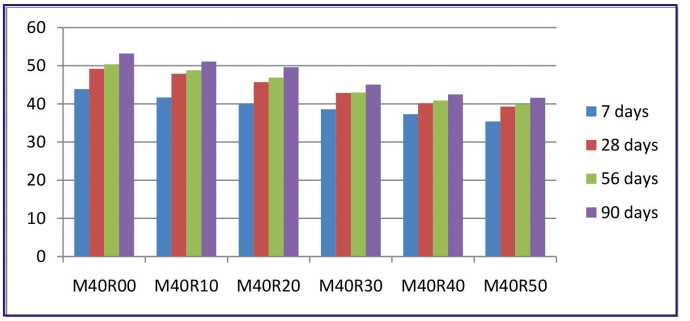

Fig. 3: Compressive Strength ofM40 Concrete with Sand Replaced By RCA (6)

Steel slag is a by-product obtained in the manufacture of steel in integrated iron and steel plants. Metallic iron contained in the slag is removed by magnetic means. It is obtained in air-cooled form and must be weathered to free lime content within limits. In addition, slag aggregates must satisfy the limit of 'volume expansion ratio' when tested as per the procedure prescribed in IS:383-2016.

Use as Coarse Aggregate

Tests were conducted on use of BF slag as part replacement of natural coarse aggregate in high strength concrete (7). The mix used 447 kg/m^3 cement, w/c ratio 0.37 and 7%silica fume. Superplasticiser was used @ 0.8 – 1.0 %, to render satisfactory workability. The compressive strength and split tensile strength were of the same order as the reference mix, up to 30% replacement by BF slag (Table 5).

Table 5: Trials with BF Slag as Coarse Aggregate (7)

Mix	Natural Coarse Aggregate Replaced by BF Slag, %	28-day compressive Strength, MPa	28-day split Tensile Strength, MPa
1	0 (Reference mix)	69.16	3.17
2	10	69.54	3.50
3	20	70.03	2.17
4	30	71.52	3.30

Use as Fine Aggregate

Coarser particles of BF slag of sand sizes have been envisaged as part replacement of natural sand in concrete (2). Starting with larger pieces of granulated slag as feed material, it is crushed and sieved in a manner similar to obtain crushed rock sand.

The resulting product conformed to grading zone II of IS: 383 (Figure 4) and particle shapes were similar to river sand (sub-angular to sub-round). Any excess of elongated particles will need processing in a Vertical Shaft Impactor (VSI) crusher. Unlike crushed rock sand, the proportion of fine fractions (< 150μ) was comparable to natural sand (<4.6%).

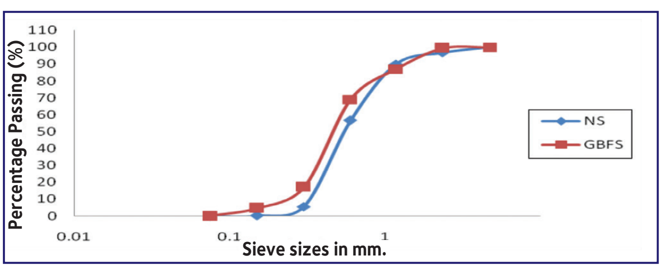

Fig. 4: Comparison of Sieve analyses of natural sand (NS) and slag sand (GBFS) (2)

Results of compressive strength of M40 grade concrete, in which natural sand was replaced in full or part by slag sand, as well as combinations with crushed rock sand or crusher dust are given in Table 6 (2). Addition of slag sand improved the compressive strength. Workability was satisfactory; in fact, mixing with crushed sand helped in achieving favourable proportion of fine fractions.

Coper Slag as Fine Aggregate

Sand-sized fraction of copper slag has been investigated as part replacement of natural sand in concrete [8]. In this investigation, copper slag conformed to grading limits, but the size fraction below 1 mm was greater than in natural sand (Figure 5).

Table 6: Compressive Strength Data on M40 Grade Concrete with Slag Sand (2).

Fine Aggregate	7 day Strength, MPa	28 day Strength, MPa
100% Natural Sand	38-42	48-52
100% crushed rock sand	40-44	50-54
100% GBS	42.9	53.3
50% GBS + 50% NS	39	52
50% GBS + 50% crushed rock Sand	40.8	52.3
50% GBS + 50% Crusher Dust	30.9	49.7

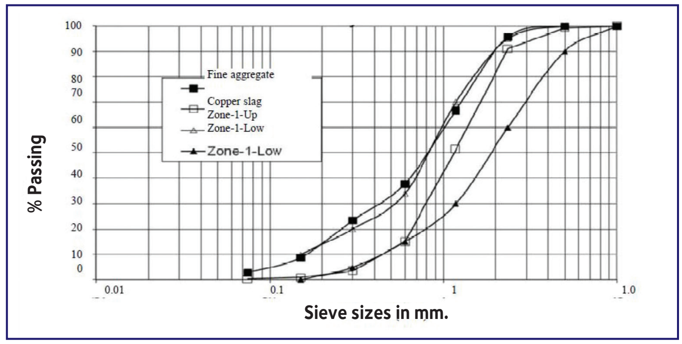

Fig. 5: Sieve Analyses of Copper Slag and Natural Sand Compared (8)

The concrete mixes had cement content 384 kg/m^3, water/cement ratio 0.6, coarse aggregate and fine aggregate contents 1136 and 712.6 kg/m^3 respectively constant, except that the fine aggregate was made up of natural sand being replaced by copper slag in increments of 20 percent. Results of slump and compressive strength are shown in Table 7 (8).

Table 7. Tests on Concrete Mixes with Copper Slag

Mix	1	2	3	4	5	6
% of copper slag in fine aggregate	0	20	40	60	80	100
Slump, mm	43	44	58	85	Collapse	Collapse
Compressive strength, MPa	36.6	35	33.4	32	30.6	28.4
Flexural strength, MPa	3.89	4.04	4.45	4.58	4.43	4.48

It can be seen that replacement of natural sand by copper slag increased the slump. This was ascribed to the glassy surface of copper slag, which absorbed less water (0.17%) than natural sand. This led to excess of free water forming internal voids, contributing to increased bleeding and porosity, weakening the strength. Gradual decrease in compressive strength with increase in copper slag percentage was noted. Flexural strength was not much affected.

Bottom Ash as Fine Aggregate

Bottom ash and fly ash are the by-products of the combustion of pulverised coal from thermal power plants. Bottom ash is the coarser material, which falls into the bottom of the furnace and constitute about 20 per cent of total ash content of the coal fed into the boilers. In view of substantial amount generated each year and already accumulated mixed with pond ash, it merits consideration.

Results of a comprehensive experimental investigations on use of bottom ash in cement and concrete, both as pozzolanic additive, and as replacement of natural sand as fine aggregate, has been reported [9]. In this series of tests, as-received bottom ash was used in part replacement of natural sand as fine aggregate. It conformed to grading zone II of IS: 383, had lower density and higher water absorption. At replacement levels up to 20 percent, the combination with natural sand was within the stipulated grading limits of zone II (Figure 6).

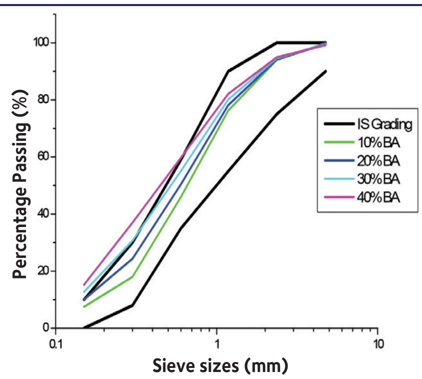

Fig. 6: Combined Grading Of Mix Of Bottom Ash And Natural Sand (9).

The details of concrete mixes and results of slump and compressive strength are in Table 8. In order to maintain the same workability at the same water content, the dosage of the superplasticiser had to be increased from 1% (in case of river sand) to 1.75% in case of 20 per cent bottom ash. It was noticed that with 20 per cent bottom ash replacing sand, the compressive strength of concrete at 28 days and later were greater than with natural sand alone [9]. This was possibly due to pozzolanic property of bottom ash, albeit much lower than fly ash from the same source.

Conclusions

Recently revised IS: 383-2016 has permitted 'manufactured' sand obtained from C&D wastes and other industrial wastes as part replacement of coarse and fine aggregate from natural sources. These can be used in plain concrete, lean concrete (≤ M15 Grade) and reinforced concrete (≤ M25 Grade). The

Table 8. Mix Proportions with Bottom Ash and Test Results

Mix	Cement, kg/m³	w/c	Sand, % Slump, mm	Comp. Strength, MPa	7d	28 d
IA	500	0.37	100	89	46.9	65.1
IB			80	73	45.3	67.3
IIA	450	450	0.4	94	40.8	59.4
IIB			80	81	40.2	62.1
IIIA	400	0.43	100	86	30.5	52.9
IIIB			80	78	29.4	55.0

research back-up is described in the paper. Manufactured aggregate should fully conform to the quality requirements and the extent of utilisation stipulated in IS: 383-2016.

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