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Performance studies on concrete with recycled coarse aggregates

Subhash C. Yaragal*, Dumpati C. Teja[a] and Mohammed Shaffi[a]

Department of Civil Engineering, National Institute of Technology, Surathkal, Karnataka, India

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Abstract. Concrete continues to be the most consumed construction material in the world, only next to water. Due to rapid increase in construction activities, Construction and Demolition (C&D) waste constitutes a major portion of total solid waste production in the world. It is important to assess the amount of C&D waste being generated and analyse the practices needed to handle this waste from the point of waste utilization, management and disposal addressing the sustainability aspects. The depleting natural resources in the current scenario warrants research to examine viable alternative means, modes and methods for sustainable construction. This study reports processing Recycled Coarse Aggregates (RCA) using a rod mill, for the first time. Parameters such as amount of C&D waste for processing, nature of charge and duration of processing time have been optimized for obtaining good quality RCA. Performance of RCA based concrete and performance enhancement techniques of 50% RCA based concrete are discussed in this paper.

Keywords: compressive strength; demolished concrete; recycled coarse aggregate; performance; performance enhancement

1. Introduction

1.1 General

Concrete is the most widely used building material in the construction industry. The wide use of concrete is due to its high compressive strength, low maintenance cost, resistant to weathering effect, economical, its excellent structural performance and above all the property of mouldability to any conceivable shape. Construction sector continues to produce and consume huge amounts of concrete, and therefore consumption of natural aggregates is significantly increasing. Two striking problems are depletion of natural aggregates and management of enormous amounts of demolished concrete (Chandra 2004). The solution for preservation of natural resources and disposal issues is to use C&D waste to the extent possible (Manzi *et al.* 2013). Last decade has witnessed enormous increase in C&D waste (Tabsh and Abdelfatah 2009, Wagih *et al.* 2013). The use of RCA in concrete is one of the ways of waste utilization (Rao *et al.* 2011).

The use of demolished waste was first carried out after Second World War in Germany (Khalaf

*Corresponding author, Professor, E-mail: subhashyaragal@yahoo.com
[a]Post Graduate Students

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and Alan 2004). Since then many countries have taken up research in this area which has shown sufficient promise. The management of C&D waste is of great concern due to increase in amount of demolition waste, dumping sites shortage, the cost of disposal and transportation, added to these is the concern of degradation of environment. The option of C&D waste utilization is not fully in practice in developing countries, due to lack of sufficient knowledge and thorough regulatory guidelines, leading to waste being piled up causing disposal issues (Silva *et al*. 2014). However, the developed countries have started looking at waste as a resource, fulfilling part of their demand for raw material (Kou *et al*. 2012). While using recycled aggregates due care should be exercised to assess the quality of aggregates, as they have different sources, grades and age (Padmini *et al*. 2009). Compressive strength mainly depends on adhered mortar, water absorption, Los Angele's abrasion, size of aggregates, strength of parent concrete, age of curing, level of replacement, interfacial transition zone, moisture etc. (Martinez-Lage *et al*. 2012). The water absorption of RCA is major factor in the strength of concrete (Panda and Bal 2013).

1.2 Characteristics of Recycled Coarse Aggregates (RCA)

1.2.1 Physical properties

The physical properties of Recycled Aggregates (RA) vary depending on the properties of parent concrete. Fairly well graded recycled aggregates can be produced using an impact crusher. The gradation range of RA is close to those of natural aggregates. The volume of adhered mortar to RA particles depends on the aggregate size and nature of parent aggregates, usually this volume ranges from 30% to 60%. Due to the adhered mortar, the density of RA particles will be lower than that of natural aggregate. The density however is in excess of 2000 kg/m^3 and is regarded as normal weight concrete.

1.2.2 Processing and grading of RCA

Most of the recycling plants use a jaw crusher for primary crushing so as to handle large pieces of concrete and residual reinforcement. Primary crusher usually reduces material down to 60-80 mm and then fed to secondary crusher. Impact crushers are preferred over cone crushers for secondary crushing as they produce higher percentage of aggregates without adhered mortar. In addition they give more rounded shape to RCA, which is beneficial for engineering performance. The material from secondary crusher passes through two screens to separate aggregates into sizes greater than 19 mm, between 19 mm and 7 mm, the material finer than 7 mm is removed and used as road metal.

Appropriate use of magnets, air knives (directed blasts of air) and hand picking are usually adopted between the two crushers to remove impurities. To aid, removal of wire reinforcement after secondary crusher additional magnets including trommels and eddy currents are adopted.

A good practice adopted in Europe, separate all materials coming to recycling plants into three distinct colour-coded groups, they are, Black: Asphalt, White: Concrete and Red: mixed waste, but generally comprised of brick. RCA is created from the "White waste". RA is produced from the "red waste" and is largely brick-based RA. RCA may sometimes be added to brick-based RA to improve the performance of the product. High asphalt content limits use in cement bound applications. This type of RA may be regarded as asphalt-based RA.

1.2.3 Treatment methods of RCA

Three treatment methods for better performance of recycled aggregate concrete are discussed by (Behera *et al*. 2014). These approaches can be grouped into three broad categories (i) Introduction of mineral admixtures such as fly ash, metakaolin, silica fume, ground granulated blast furnace slag and nano silica. These mineral admixtures act as micro-filler, filling the ITZ between the aggregate surface and the matrix. This reduces the porosity of concrete and helps in enhancing the strength and durability, (ii) Impregnation of RA in cement slurry or other mineral admixture solution or surface coating of RA with low w/c ratio paste or by impregnating RA in silica fume solution or in other mineral admixture solution also helped in healing the pores or cracks in RA and (iii) Modifying mixing process.

1.3 Important studies on Recycled Coarse Aggregates (RCA)

Performance tests have been carried out by Sagoe-Crentsil *et al.* (2001) for fresh and hardened properties of concrete made with commercially produced coarse recycled concrete aggregate and natural fine sand. Test results indicate that the difference between the characteristics of fresh and hardened recycled aggregate concrete and natural aggregate concrete is perhaps relatively narrower than reported for laboratory crushed recycled aggregate concrete mixtures.

C&D waste generated scenario worldwide have been briefly reviewed by (Rao *et al.* 2007), RA produced from C&D waste and their utilization in concrete and governmental initiatives towards recycling of C&D waste. Further an overview of the properties of recycled aggregates and the effect of their use on the properties of fresh and hardened concrete are also presented.

Use of recycled aggregates in concrete would reduce its compressive strength and render the concrete less durable. Various methods by Kou and Poon (2012) have been attempted to compensate for the lower quality of the recycled aggregates for concrete production. The effects of incorporating class F fly ash in the concrete mix design to mitigate the lower quality of recycled aggregates in concrete is presented. One of the practical ways to utilize a high percentage of recycled aggregate in concrete is by incorporating 25-35% of fly ash since some of the drawbacks induced by the use of recycled aggregate in concrete could be minimized.

Valuable information on the durability effects and design method for RAC have been studied by Kwan *et al.* (2012). Parameters like compressive strength, UPV, shrinkage, water absorption and intrinsic permeability have been examined. The results reveal that the RAC exhibits a good UPV value, lower water absorption and low intrinsic permeability. The target strength was achieved even when 80% of the total coarse aggregate content was replaced by the RCA and the mix design method proposed by the Department of Environment (DoE), United Kingdom was used.

Review by McNeil *et al.* (2013) report that aggregate properties are most affected by the residual adhered mortar on RCA. Because of this, RCA is less dense, more porous, and has a higher water absorption capacity than natural aggregates. While RCA and NA have similar gradation, RCA particles are more rounded in shape and have more fines broken off in Los Angele's abrasion and crushing tests. Replacing NA in concrete with RCA decreases the compressive strength, but yields equivalent or superior splitting tensile strength. The modulus of rupture for RCA concrete was less than that of conventional concrete, likely due to the weakened interfacial transition zone from residual mortar. The modulus of elasticity is also lower than expected, caused by the more ductile aggregate.

The suitability of using two types of water-reducing admixtures to improve the characteristics of concrete made with recycled aggregates has been studied by Barbudo *et al.* (2013). Four series of concrete with various replacement ratios (0%, 20%, 50% and 100%) of natural aggregates by coarse recycled concrete aggregates were manufactured and used without admixtures, with a traditional plasticizer and a high-performance plasticizer. Their results show that a substitution of 100% natural aggregates is possible without affecting the major mechanical properties, adopting suitable water-reducing admixture.

Long-term study on the mechanical and durability properties of concrete prepared with 0%, 50% and 100% recycled concrete that were cured in water or outdoor exposure conditions for 10 years, has been reported by Kou and Poon (2013). Recycled aggregate concrete was prepared by using 25%, 35% and 55% class F fly ash, as cement replacements. It was found that, after 10 years, the compressive strength and modulus of elasticity of the concrete prepared with 100% recycled concrete aggregate was still lower than that of the control concrete. Fly ash improved the resistance to chloride ion penetration but it also increased the carbonation depth of concrete. This study suggest that the optimal mix proportions for RCA mixtures are: 50% RA as replacement of natural aggregates and 25% fly ash as a replacement of OPC.

Studies by Belin *et al.* (2014) suggest that water absorption of RCA at 24 hours can be seen as the simple sum of the capillary absorption of both residual cement paste and initial natural aggregates. They have proposed tentative frame for a classification of RCA, based on water absorption rate and water absorption capacity at 24 hours.

Additional amount of cement was used by Beitran *et al.* (2014) to compensate for the effect of the recycled aggregates and to obtain properties that are similar to those of conventional concrete. These report that to obtain desired compressive strength of concretes containing 100% recycled concrete aggregates, 12% cement (by weight) should be added to the concrete mixture.

The use of RCA as coarse aggregate in concrete mixes resulted in a decrease in the strength depending on the replacement ratio and the grade of concrete. The use of steel slag as 67% replacement of RCA enhanced the strength as reported by Qasrawi (2014). Mukharjee and Barai (2015), have reported improved mechanical performance of RCA based concrete with incorporation of 3% Nano-Silica. Studies by Shaikh *et al*. (2015) also report improved performance of high volume fly ash-recycled aggregate concrete with micro-silica as replacement to Ordinary Portland Cement. Prusty *et al*. (2015) have shown that Taguchi method is an efficient tool to rank the important parameters controlling the strength of concrete. The w/c ratio is ranked one followed by Nano-Silica have more influence as compared to other two factors namely RCA and maximum cement content.

This study reports some important methods of characterization of RCA and also recommend performance enhancement studies on RCA based concrete.

2. Materials

2.1 Materials

Ordinary Portland Cement (OPC) 43 grade was used and its properties are tabulated in Table 1. Coarse aggregate was crushed stone with a maximum size of 20 mm. Locally available Natural River sand conforming to zone I (IS 383-1970 grading requirements) was used as fine aggregate. Physical properties of fine and coarse aggregates are presented in Tables 2, 3, 4, and 5 respectively. Potable quality water is used. Recycled aggregates were obtained from demolished concrete. This source of demolished concrete was produced by crushing the 28 days cured 150 mm concrete cubes. This was produced in the laboratory with maximum size of 20 mm.

Table 1 Physical properties of Ordinary Portland Cement

Sl. no.	Property	Result obtained			Requirements as per IS code			Remarks
1	Specific gravity	3.10			--			OPC 43 grade
2	Normal consistency	31%			--			
3	Setting times, minutes	Initial 65 Final 270			Not less than 30 Not more than 600			Satisfies IS code requirements.
4	Fineness, m^2/kg	330			Not less than 300			
5	Soundness, mm	2.50			Not more than 10 mm			
6	Compressive strength, MPa	3 days	7 days	28 days	3 days	7 days	28 days	
		28	36	48	22	33	43	

Table 2 Sieve analysis of fine aggregates

IS sieve size	Percentage passing	IS 383-1970 Sieve analysis of fine aggregate				Remarks
		Zone 1	Zone 2	Zone 3	Zone 4	
10 mm	100	100	100	100	100	Satisfies Zone-I grading requirements
4.75 mm	99.5	90-100	90-100	90-100	95-100	
2.36 mm	95.0	60-95	75-100	85-100	95-100	
1.18 mm	69.0	30-70	55-90	75-100	90-100	
600 μ	29.3	15-34	35-59	60-79	80-100	
300 μ	5.3	5-20	8-30	12-40	15-50	
150 μ	2.8	0-10	0-10	0-10	0-10	

Table 3 Properties of fine aggregates

Property	Result
Specific gravity	2.62
Bulk density	Loose: 1463 kg/m^3 Compact: 1661 kg/m^3
Moisture content	Nil

Table 4 Sieve analysis of coarse aggregates

IS sieve size	Percentage passing	IS:383-1970 Grading requirements		Remarks
		(I) Percentage passing for single sized aggregates	(II) Percentage passing for graded aggregates	
40 mm	100	100	100	Single sized aggregate
20 mm	95.6	85-100	95-100	
10 mm	2.4	0-20	25-55	
4.75 mm	0	0-5	0-10	

Table 5 Properties of coarse aggregates

Property	Result
Specific gravity	2.73
Bulk density	Loose: 1360 kg/m^3 Compact: 1527 kg/m^3
Moisture content	Nil

2.2 Processing and characterization of RCA

Processing or extracting RCA from demolished concrete involves, separating the adhered mortar, to the extent possible to bring the physical properties of RCA closer to or similar to that of virgin/natural aggregates. For the first time, a rod mill as shown in Fig. 1, is being utilized for processing of RCA.

Fig. 1 Rod mill machine

The recycled coarse aggregates were obtained from the laboratory produced concrete after attaining the 28 day strength. They are extracted from the concrete matrix by using the hydraulic machine to break the concrete into smaller pieces in the range of 20 mm to 40 mm. These pieces will be having a high content of old mortar attached to it which is not desirable for them to be used as coarse aggregates. Separation of this adhered mortar was the main challenge in obtaining the RCA which should have similar properties closer to that of fresh/virgin aggregates after processing.

Fig. 1, shows the details of a rod mill used for processing RCA. The machine consists of a cylindrical can of 230 mm diameter and a length of 220 mm. It is placed on two parallel shafts which are separated by a small distance. One of this shaft is connected to motor. Can is placed in such a way that longitudinal axis of the can is parallel to that of shafts. When power is supplied single shaft starts rotating which in-turn rotates the can and the second shaft starts rotating automatically. This resembles the gear mechanism in a analog watch. This explains the mechanism of the machine.

Table 6 Properties of recycled coarse aggregates

Sl. no.	Property	Results
1	Specific gravity	2.59
2	Water absorption	2.69%
3	Fineness modulus	6.96

Table 7 Sieve analysis results of natural and recycled coarse aggregates

Sieve size (mm)	% Finer	
	NCA	RCA
20	100	100
16	68.5	71.5
12.5	32.1	27.7
10	0.7	0.5

(NCA-Natural Coarse Aggregates, RCA-Recycled Coarse Aggregates)

This can consists of steel rods of different desired dimensions which can process the material placed in it once it starts rotating. This can has a capacity of only 5 kg in terms of material to be used in each cycle. Thus, in addition to rods some steel balls were also used to increase the efficiency of processing in the available space inside the can. As this machine was being used for the first time to process recycled aggregate, it was necessary to decide on the charge to be used in terms of number of steel rods and its dimensions. Also the amount of broken concrete to be used for each cycle was to be evaluated. If the charge used is more than optimum it results in wear and tear of aggregates. Thus there were many aspects to be taken care of and optimized before processing concrete. Three different sets of experiments were conducted to decide the charge to be used, amount of aggregate to be used, the processing time for each cycle. Water absorption test was the basis for deciding the quality of processed recycled aggregates. These results are presented in section 4. Thus the recycled aggregate is obtained using rod mill machine with the above parameters.

Table 6 shows the properties of recycled coarse aggregate. Sieve analysis results of natural and recycled coarse aggregates are presented in Table 7.

2.3 Water

Water is an important ingredient of concrete as it actively participates in chemical reaction with cement. The quantity of water used should be just sufficient for hydration and suitable workability of concrete. In present investigation the potable water is used.

2.4 Copper slag

Copper slag is a by-product created during the copper smelting and refining process. As refineries draw metal out of copper ore, they produce a large volume of non-metallic dust, soot, and rock. Collectively, these materials make up slag. One of the primary advantages to copper slag is the low risk it poses to health and the environment. Copper slag is bought from a local supplier which is normally used for the blasting of pipes. The gradation properties of copper slag satisfies zone-I grading requirements of river sand, which is used as a replacement to river sand.

2.5 Iron Ore Tailings (IOT)

Mine tailing is one of the waste materials generated from the mining industry and was collected from tailing dam situated in Kudremukha, Karnataka, India. Tailing samples were taken at a depth of 0.90 m below the surface in the tailing dam and then transported to the laboratory in sealed bags in laboratory; the tailings were air dried in shade and were stored in non-corrodible bins for further investigation. It is observed that the fines percentage is very less and sand proportion is very significant from the sieve analysis results, tailings satisfied codal requirements confirming to zone III of IS: 383:1970, which is also used as a replacement material to river sand.

2.6 Silica fume

Silica fume used in this study belongs to CORNICHE SF brand. It is recommended to be used with any compatible high range water reducing admixture to provide maximum workability maintaining the desired low water/binder ratio.

2.7 Nano silica

Nano Silica used here belongs to Cemsyn brand. Cemsyn is a series of silica based binders/fillers used in the cementing and concreting operations to impart different properties to the resultant compositions. Nano silica particles when added to concrete make it easier to pump and present no segregation problems. They also help in reducing the amount of binder in each concrete mix and give better results. Nano fillers enter micro and nano pores and give denser concrete which has a high resistance to sulfate and chloride attacks, is less permeable.

2.7 Mix adopted

Nominal mix design of 1:1.5:3 was adopted in the present study. Water cement ratio is found to be 0.46 after trial and error experiments with different w/c ratios so as to achieve slump in the range of 50 to 75 mm.

3. Experimental methodology

About 80 No's of 150 mm concrete cubes of nominal mix (1:1.5:3) were cast in the laboratory and crushed to failure after 28 days of water curing, Later this crushed concrete is processed to obtain recycled coarse aggregates. Crushed concrete fragments were broken using a hammer into small pieces of size compatible for processing, using adequate equipment, such as rod mill. Parameters to be adopted in processing and characterization of recycled coarse aggregates using rod mill machine is decided based on different sets of experiments designed. The processed RCA is adopted in further experiments.

For performance studies, cubes were cast with different proportions of recycled coarse aggregate as 0%, 25%, 50%, 75%, and 100%. For each mix 3 Nos. of 150 mm concrete cubes were cast and 28 days water cured and then tested for their compressive strengths. Concrete cubes with same water cement ratio and different proportions of copper slag as 0%, 25%, 50%, 75%, 100% replacing river sand were cast as 3 cubes for each mix and compressive strength is obtained after 28 days of curing. Similar experiments with iron ore tailings were planned.

For performance enhancement studies, cubes were cast keeping the recycled aggregate constant as 50% and varying copper slag in proportions of 0%, 25%, 50%, 75%, and 100% with 3 cubes for each mix. Similarly experiments were conducted for different proportions of iron ore tailing as

Table 8 Concrete mix proportions per cubic meter of concrete

Mix	RCA (%)	C (kg)	FA (kg)	CA (kg)	RCA (kg)	W (kg)
Mix 1	0	404	606	1212	-	198
Mix 2	25	404	606	909	303	201
Mix 3	50	404	606	606	606	203
Mix 4	75	404	606	303	909	205
Mix 5	100	404	606	-	1212	205

(RCA-Recycled Coarse Aggregates, C-Cement, FA-Fine Aggregates, CA-Coarse Aggregates, W-Water)

Table 9 Concrete mix proportions per cubic meter for RCA+CS

Mix	RCA (%)	Copper slag		C (kg)	FA (kg)	CA (kg)	RCA (kg)	W (kg)
		(%)	(kg)					
Mix 1	50	0	-	404	606	606	606	203
Mix 2	50	25	152	404	454	606	606	204
Mix 3	50	50	303	404	303	606	606	205
Mix 4	50	75	454	404	152	606	606	206
Mix 5	50	100	606	404	-	606	606	207

Table 10 Concrete mix proportions per cubic meter for RCA+CS+SF

Mix	RCA (%)	Copper slag		Silica Fume		C (kg)	FA (kg)	CA (kg)	RCA (kg)	W (kg)
		(%)	(kg)	(%)	(kg)					
Mix 1	50	0	-	5	16.2	383.8	606	606	606	203
Mix 2	50	25	152	5	16.2	383.8	454	606	606	204
Mix 3	50	50	303	5	16.2	383.8	303	606	606	205
Mix 4	50	75	454	5	16.2	383.8	152	606	606	206
Mix 5	50	100	606	5	16.2	383.8	-	606	606	207

0%, 25%, 50%, 75%, and 100%.

Experiments were also planned to study the further performance enhancement of 50% RCA based concrete to achieve strength at least equal to or greater than those of no RCA based concrete.

Cement is replaced by 5% silica fume and cubes were cast keeping the recycled aggregate constant as 50% and varying copper slag in proportions of 0%, 25%, 50%, 75%, and 100% with 3 cubes for each mix. Similarly experiments were conducted for different proportions of iron ore tailing as 0%, 25%, 50%, 75%, and 100% separately with 5% nano silica, replacing OPC and replacing NA to 50% RCA. These cubes were kept for 28 days curing and were tested for compressive strength. Based on analysis of results obtained, important conclusions are drawn.

3.1 Test matrix

Tables 8, 9 and 10, presents the compositions of various concrete mixes designed to achieve the objectives set forth. The additional amount of water for mixes 2-5, is to accommodate for surface absorption of RCA.

3.2 Slump tests

Initial experiments are conducted to get a slump of at least 50-75 mm without super plasticizers. Standard slump cone apparatus is used for measuring the value of slump. Slump test is done for virgin concrete to decide the water cement ratio to be adopted. As the water cement ratio is constant, chemical admixtures are used in the later experiments done with different proportions of recycled aggregate, copper slag, iron ore tailings, silica fume and nano silica to achieve the desired workability in the range of 50-75 mm, for performance evaluation.

4. Results and discussion

4.1 Processing of recycled aggregate

The quality of recycled aggregate from C&D waste essentially depends on the technique of processing involved in obtaining recycled aggregate. As mentioned in the previous section, for processing recycled aggregate, a rod mill has been used, preliminary experiments were undertaken to optimize on working parameters such as amount of C&D waste for each run to be used, variation in the nature of charge such as only rods, only steel balls, and a combination of the two for abrasion, and also the time or duration of run. Post water absorption determination of processed recycled aggregate was the basis to decide on the quality of processing. The lower the 24 hours water absorption, the better is the quality of recycled aggregate processed. The following three experiments were designed and conducted to obtain the most favorable operational conditions, required for achieving the most suitable processing.

4.1.1 Experiment 1

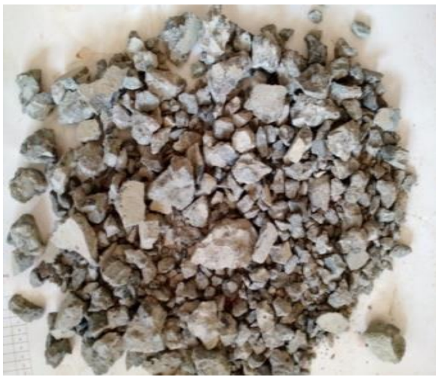
To determine the quantity/amount of C&D material to be used for each run, construction & demolished material as multiples of weight of charge is considered. Optimum quantity of raw C&D material is decided based on the values of water absorption of the recycled aggregates being processed. Table 11 presents the results obtained.

Fig. 2 shows the quality of aggregates before and after processing. From Table 11, it is clear that best processing occurs for 5 kg of C&D waste.

Table 11 Water absorption results for various weights of C&D waste

Sl. no	Material weight (kg)	Charge (kg)	Water absorption (%)
1	0.84	0.84	2.24
2	1.68	0.84	2.16
3	2.52	0.84	2.00
4	3.36	0.84	1.89
5	4.20	0.84	1.93
6	5.04	0.84	1.25

(a) Virgin aggregates



(b) Broken concrete fragments

(c) Processed concrete, without washing and sun-drying

(d) Recycled aggregates after washing and sun-drying

Fig. 2 Aggregates before and after different stages of processing

4.1.2 Experiment 2

To find the charge to be used in each cycle, charge is divided into three sets as A, B and A+B.

The available charge materials for abrasion are steel balls each weighing 70 g and steel rod each weighing 60 g.

Charge A- 12 balls–840 g

Charge B- 14 rods–840 g

Charge A+B–6 balls+7 rods–840 g

The processing time adopted being 30 minutes.

Fig. 3 shows the quality of aggregates before and after processing. From Table 12, it is clear that best processing is possible by use of 14 Nos of rods, each weighing 60 g.

Table 12 Water absorption results for various types of charges tried

Sl. no.	Material (kg)	Charge type	Water absorption (%)
1	2.000	A	1.60
2	2.000	B	1.40
3	2.000	A+B	1.50

(a) Virgin aggregates

(b) Broken concrete fragments

(c) Processed concrete, without washing and sun-drying

(d) Recycled aggregates after washing and sun-drying

Fig. 3 Aggregates before and after processing

4.1.3 Experiment 3

Time required for processing is decided based on the water absorption values of aggregates obtained after three different time intervals. Time intervals for study are decided as 30 min, 45 min, and 90 min.

Fig. 4, shows the quality of aggregates after processing for different intervals of time. From Table 13, it is clear that processing time of 30 minutes is optimum.

The optimized methodology is adopted to obtain RCA, which are only used in cube casting for performance based studies and also for performance enhancement studies.

Table 13 Results of water absorption for various processing times

SL. no.	Material weight (kg)	Charge	Processing time (min)	Water absorption (%)
1	2.000	B	90	2.0
2	2.000	B	45	1.9
3	2.000	B	30	1.4

(a) 30 minutes

(b) 45 minutes

(c) 90 minutes

Fig. 4 Aggregates after processing for 30 min, 45 min, and 90 min

4.2 Compressive strength

Compressive strength testing of all specimen were carried out as per IS: 516-1959. The load was applied without shock at a rate of 140 kg/cm^2/min. A set of three cubes were tested for each mix, for each percentage of RCA replacement. The maximum load resisted divided by cross sectional area of specimen, gave the compressive strength. Average of three specimen were taken, provided the individual variation in strength was not more than ±15% of the average, and the results were tabulated and interpreted.

4.2.1 Strength variation with different proportions of RCA (RCA based concrete)

The results of the compression tests for concrete with varied proportions of RCA are presented in Fig. 5(a) and (b). It is observed that the compressive strength decreases with increase in percentage of the RCA replacement. For control mix without RCA, the compressive strength being 32.7 MPa and it reduced to 25.9 MPa for 100% RCA based concrete. There is nearly 20% strength reduction with 100% RCA based concrete. The present results are in agreement with other investigators.

A fall in the compressive strength is reported by Crentsil *et al*. (2001). Tabsh and Abdelfatah (2009) have reported that the decrease in strength is by about 10-25%. These findings are similar to the results of Kou and Poon (2013). A decline in their compressive strength is also reported by Qasrawi (2014) and Barbudo *et al.* (2013). Kou and Poon (2012) have also reported a reduction in concrete strength when replaced with RCA. A reduced compressive strength, flexural strength and split tensile strength of concrete with increase in the amount of RCA is also reported by Padmini *et*

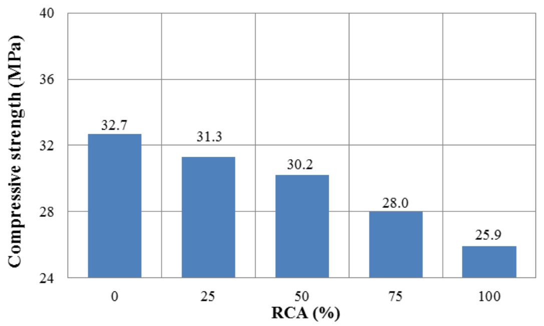


Fig. 5(a) Strength variation of concrete with varied proportions of RCA

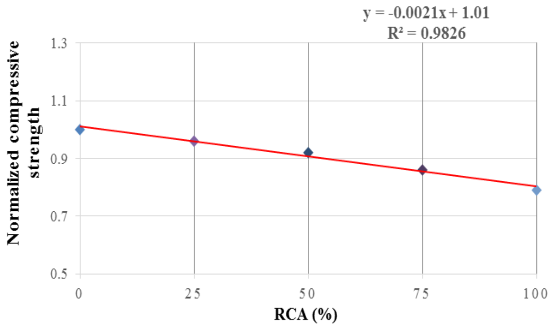


Fig. 5(b) Normalized strength variation of concrete with varied proportions of RCA

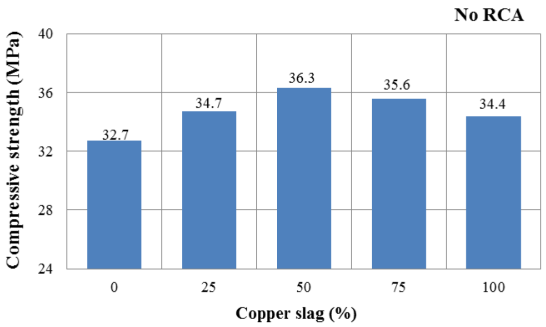


Fig. 6(a) Strength variation of concrete with varying proportions of copper slag

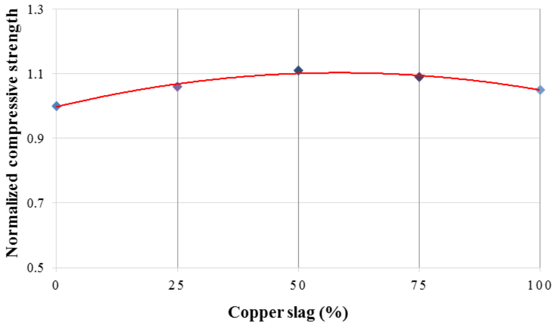


Fig. 6(b) Normalized strength variation of concrete with copper slag

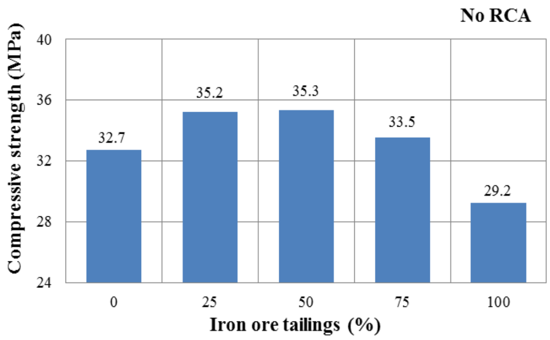


Fig. 7(a) Strength variation of concrete with varying proportions of Iron ore tailings

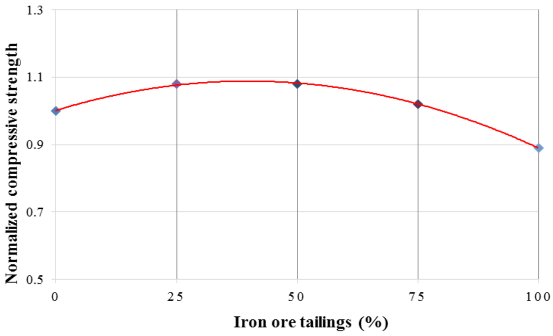


Fig. 7(b) Normalized strength variation of concrete with iron ore tailings

al. (2009).

In sections 4.2.2 and 4.2.3 experiments were conducted to study the strength variation of normal concrete without RCA, but with fine aggregate being replaced partly/fully with copper slag or iron ore tailings.

4.2.2 Strength variation with part/full replacement of fine aggregate with copper slag (normal concrete, no RCA)

Experiments were conducted to study the strength variation of normal concrete without RCA, but with fine aggregate being replaced partly/fully by copper slag. Cubes were cast by replacing fine aggregate with that of copper slag at different proportions and strength of those cubes were found after 28 days of curing. The results of the 28 days cube compressive strengths, are presented in Fig. 6(a) and (b).

Fig. 6(a) and (b), presents the strength variation results with different proportions of copper slag replacing river sand. It is observed that strength increases up to 50% replacement level and thereafter it decreases, however it is still in excess by 5% up to 100% replacement when compared to the case of no RCA based concrete.

Table 14 Relative strength factors for various levels of RCA, copper slag, and IOT

Percentage replacement (%)	Strength variation		
	RCA for virgin CA	Copper slag for FA	Iron ore tailings for FA
0	1.00	1.00	1.00
25	0.96	1.06	1.08
50	0.92	1.11	1.08
75	0.86	1.09	1.02
100	0.79	1.05	0.89

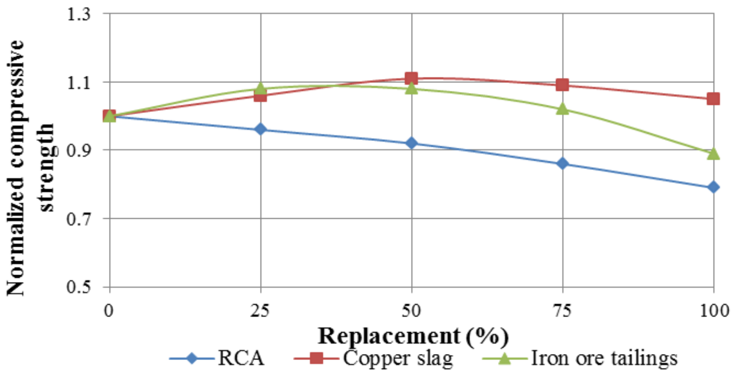


Fig. 8 Strength ratio Vs replacement levels RCA, copper slag, iron ore tailings

4.2.3 Strength variation with part/full replacement of fine aggregate with iron ore tailings (normal concrete, no RCA)

Experiments were conducted to study the strength variation of normal concrete without RCA, but with fine aggregate being replaced partly/fully by iron ore tailings. Fig. 7(a) and (b), presents the variation in strength with different proportions of iron ore tailings replacing river sand. It is observed that strength increases up to 50% replacement level and thereafter it decreases, but even at 75% replacement level, the strength of concrete is more than that of no RCA based concrete.

4.2.4 Summary of strength variation and prediction equations

Table 14 presents the results as relative strength factors for various levels of RCA replacements and copper slag in place of FA and also for the case of IOT in place of FA.

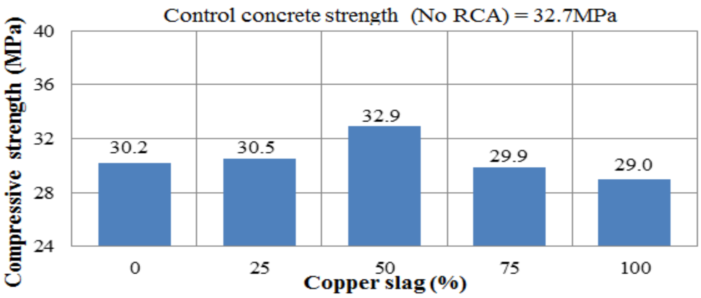


Fig. 9 Strength variation of 50% RCA based concrete with copper slag

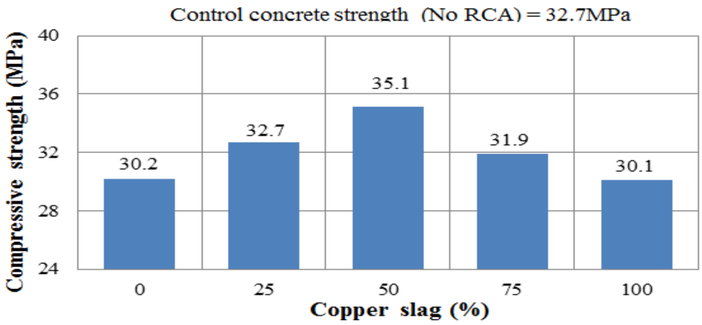


Fig. 10 Strength variation for 50% RCA concrete & 5% silica fume, with copper slag

Fig. 8 shows decrease in strength with increase in RCA replacement. Strength variation of concrete with varied levels of copper slag and iron ore tailings is also presented. The following equations are proposed for strength increase/decrease. These equations can be used to predict the Normalized Compressive Strength (NCS) of concrete as a function of either RCA or copper slag or IOT replacement levels, with maximum error in prediction of less than 5%.

$$\text{For RCA based, NCS of concrete} = -0.0021\,x + 1.01 \tag{1}$$

$$\text{For copper slag based, NCS of concrete} = -3\times10^{-5}x^2 + 0.0036\,x + 0.9974 \tag{2}$$

$$\text{For iron ore tailings based, NCS of concrete} = -5\times10^{-5}x^2 + 0.0044\,x + 1.0014 \tag{3}$$

Where for Eq. (1), x is % of RCA (CA replaced with RCA) and for Eqs. (2) and (3), x is % of FA/sand (FA/sand replaced with copper slag/IOT).

4.3 Performance studies for RCA based concrete

4.3.1 Usage potential of 50% RCA with variation in fine aggregate replacements by copper slag

Here the recycled aggregate percentage is kept constant at 50% and copper slag is varied from 25% to 100%. From Fig. 9 it is observed that use of 50% RCA and replacement of fine aggregate by 50% with copper slag would give concrete strength equal to or more than that of control mix, i.e., 32.7 MPa for no RCA based concrete.

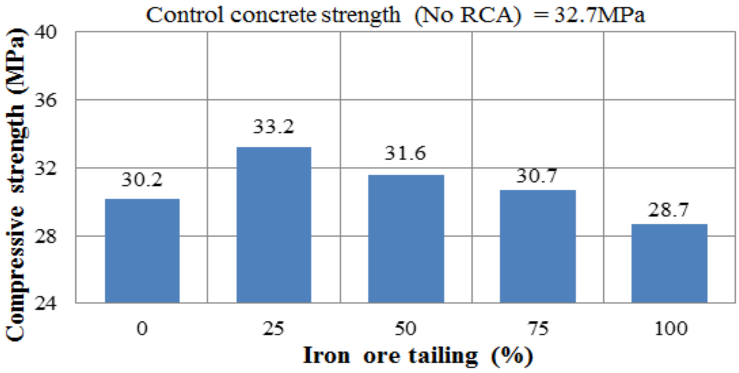


Fig. 11 Strength variation of 50% RCA concrete with iron ore tailings

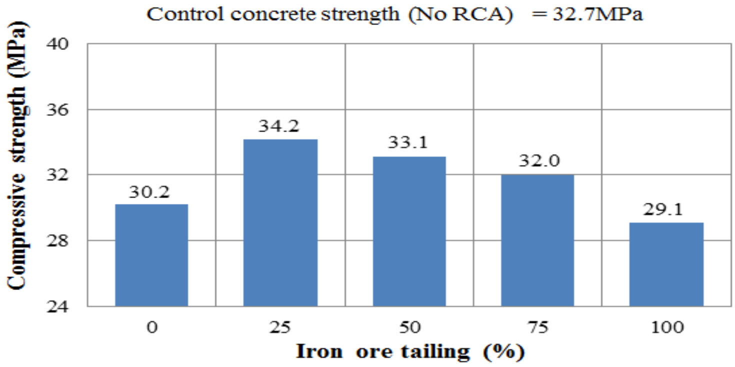


Fig. 12 Strength variation for 50% RCA concrete & 5% nano silica, with IOT

4.3.2 Usage potential of 50% RCA with variation in fine aggregate replacements by copper slag and use of silica fume

Silica fume is introduced in this set of experiments in order to achieve more strength than the previous set of experiments. Silica fume is maintained constant at 5% replacement of cement along with recycled aggregate constant at 50% and copper slag is varied to find out the optimum percentage of replacement. From Fig. 10, it is clear that the control concrete strength is achievable with 5% silica fume, 50% RCA & 25% copper slag.

4.3.3 Usage potential of 50% RCA with variation in fine aggregate replacements by iron ore tailings

Here the recycled aggregate percentage is kept constant at 50% and iron ore tailings is varied from 25% to 100%. From Fig. 11, it is seen that for, 50% RCA & 25% iron ore tailings would give strength equal to that of control mix.

4.3.4 Usage potential of 50% RCA with variation in fine aggregate replacements by iron ore tailings and nano silica

Nano silica is introduced in this set of experiments in order to achieve more strength than the previous set of experiments. Nano silica is maintained constant at 5% replacement of cement along with recycled aggregate constant at 50% and iron ore tailings is varied to find out the optimum percentage of replacement. From Fig. 12, it is clear that the strength is achievable with 5% Nano silica, 50% RCA & 50% iron ore tailings.

5. Conclusions

- For the first time a rod mill is used for processing and characterization of recycled coarse aggregates.
- Parameters such as weight of C&D waste for processing, nature of charge and duration of processing time were optimized for obtaining recycled coarse aggregates from C&D waste.
- Quality of recycled aggregate plays a vital role in the performance of RCA based concrete. As the degree of processing gets better and better the recycled aggregate tends to be closer to virgin/natural aggregate by way of its surface texture.
- A maximum reduction in compressive strength of about 21% was noticed when the entire natural/virgin aggregate was replaced with RCA.
- Two independent approaches on normal concrete (no RCA) of partly replacing FA by either copper slag or iron ore tailings is studied for strength variation. At all levels of copper slag replacing FA, there is an increase in strength of concrete, maximum being 11%. On the other hand IOT replacing FA up to 75% has shown favorable increased strength results, maximum being 8%.
- Two performance enhancement techniques to improve strength of 50% RCA based concrete to achieve strength either equal to or more than that of no RCA based concrete, are proposed they are (i) adopting 50% replacement of FA by copper slag and 5% replacement of OPC by silica fume and (ii) adopting 50% replacement of FA by IOT and 5% replacement of OPC by nano silica.

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