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Usage potential of recycled aggregates in mortar and concrete

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Abstract. With the rapid growth in construction sector, it becomes all the more important to assess the amount of Construction and Demolition (C&D) waste being generated and analyze the practices needed to handle and use this waste before final disposal. This serves waste management and disposal issues, paving way to waste utilization in construction industry from the sustainability point of view. C&D waste constitutes a major bulk of total solid waste produced in the world. In this work, an attempt is made to study the performance of concrete using water soaked Recycled Coarse Aggregates (RCA) in replacement levels of 0%, 25%, 50%, 75% and 100% to Natural Coarse Aggregates (NCA). Experiments were designed and conducted to study the performance of RCA based concrete. Further suitable performance enhancement techniques to RCA based concrete were attempted, to achieve compressive strength at least equal to or more than that for no RCA based concrete (control concrete). Performance enhancement study is reported here for 50% and 100% RCA based concretes. All four techniques attempted have given favorable results encouraging use of RCA based concretes with full replacement levels, to adopt RCA based concrete in structural applications, without any kind of concern to the stake holder. Further attempts have also been made to use Recycled Fine Aggregates (RFA) with appropriate modifications to serve as fine aggregates in mortar and concrete. Using RFA blended with river sand fractions as well as RFA with Iron Ore Tailings (IOT) fractions, have given good results to serve as fine aggregates to the extent of 100% replacement levels in mortars and concretes.

Keywords: recycled aggregates; recycled concrete; recycled mortar; performance; performance enhancement

1. Introduction

1.1 General

Severe demand for land to house alarming population increase needs in recent years, in India and all over the world, has resulted in remarkable waning of the natural aggregates resources day by day. On the other hand, millions of tonnes of Construction and Demolition (C&D) residues are generated all over the world in the last decade. Construction and demolition waste disposal has also emerged as a problem in India. C&D waste and more specifically concrete has been seen as a

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resource in developed countries. Therefore, the recycling of waste concrete is beneficial and necessary for the environmental preservation and for effective utilization of natural resources. The use of recycled coarse aggregates and fine aggregates obtained from construction and demolition waste in new concrete is one of the viable solution for effective waste utilization.

The management of C&D waste is a major challenge and concern as enormous quantity of demolition waste being produced, resulting on environmental degradation. Though some of the construction materials could be substituted by reprocessed waste material, these options are not being practiced in developing countries due to insufficient knowledge and lack of strict regulatory frameworks leading to waste getting piled up posing disposal problems. However, developed countries have been considering this waste as a resource and have fulfilled a part of their demand for raw material. Utilization of RA in concrete is becoming more common in developing countries like India, these days but for lower grade applications. Research efforts are on, to produce higher grade concrete incorporating RA.

1.2 Construction and demolition (C&D) waste

Whenever any construction/demolition activity associated with buildings, roads, flyovers, remodeling etc, takes place construction and demolition waste is generated. Waste material usually consists of inert and non-biodegradable material like concrete, plaster, metal etc. Items such as bricks, wood, tiles, metal are recycled, concrete and masonry waste which is more than 50% of the waste from C&D activities are not being currently recycled in India. However countries like UK, USA, France, Denmark, Germany and Japan, practice recycling of concrete and masonry waste. Concrete and masonry waste can be recycled by sorting, crushing and sieving into recycled aggregate. C&D waste needs to be focused upon in view of (i) The potential to save natural resources, (ii) Its bulk which is carried over long distances for just dumping, (iii) Its occupying significant space at landfill sites, and (iv) Its presence spoils processing of biodegradable as well as recyclable waste.

Many developed countries have been recycling C&D waste and using it for construction works. In Scotland about 63% of the C&D waste was recycled in 2000. The Government there is working out specifications and code of practice for recycling of C&D waste. U.K. uses 49-52% of the C&D wastes and Australia reuses 54% of the wastes generated. Belgium has a higher recycling rate (87%) and uses majority of C&D for recycling purposes. Japan is one of the pioneer countries that recycle C&D waste 85 million tonnes of C&D waste was generated in 2000, of which 95% of concrete was crushed and reused (Rao *et al.* 2007).

In India, there is not much development in this field. In the international experiences cited above, there is considerable emphasis on recycling of C&D waste in India.

1.3 Recycled coarse aggregate (RCA)

The compressive strength of RCA based concrete depends on adhered mortar, water absorption, Los Angele’s aggregate abrasion, size of aggregates, strength of parent/original concrete, age of curing, and ratio of replacement, interfacial transition zone, impurities present etc. Aggregates from different sources, exhibit different engineering properties, therefore using recycled aggregates as a source of natural aggregates will require checking the quality of aggregates, since they are collected from different sources, grades of concrete and age. Thorough evaluation of properties of recycled aggregates is necessary before using them in making concrete.

Martinez-Lage *et al.* (2012) have reported a study on the behavior of concrete made with mixed recycled coarse aggregate, with a high percentage of fired clay (brick and similar) waste. De Brito *et al.* (2005) have reported that the decline in compressive strength in such concrete was of the order of 45%, and in bending strength around 26%, confirming that concrete could be manufactured with mixed recycled aggregate. The authors added that since the primary problem was absorption, it was advisable to soak the aggregate before use.

Rahal (2007) has conducted experimental studies on some of the mechanical properties of recycled aggregate concrete as compared to those of the conventional normal aggregate concrete. Rao *et al.* (2007) have discussed the international practices associated with use of recycled aggregates from C&D waste in concrete and also the governmental initiatives as regards to C&D waste recycling. Tabsh and Abdelfatah (2009) have done a study on the influence of recycled aggregate on strength properties of concrete.

Kou and Poon (2012) have reported that incorporation of about 25-35% of class F flyash in concrete would compensate for some of the strength reduced effect of using RCA in concrete. Kou *et al.* (2011) have also studied the performance of RCA based concretes with incorporation of mineral admixtures such as silica fume, metakaolin, flyash and ground granulated blast furnace slag. They have reported that the properties of RCA based concrete improve with incorporation of mineral admixtures. Padmini *et al.* (2009) have done a study on influence of parent concrete on the properties of RAC. They have conducted studies with three parent concrete strengths and each having a maximum size of aggregates 10 mm, 20 mm and 40 mm, making a total of 9 samples. Zhu *et al.* (2013) have investigated the durability properties of recycled aggregate concrete treated with silane-based water repellent agents. Kou and Poon (2013) have reported the mechanical and durability properties of RCA based concrete (0%, 50% and 100% replacement levels) exposed to 10 years duration. Their study showed that though flyash improved resistance to chloride ion penetration but the carbonation depth also increased.

Qasrawi (2014) has concluded that the use of RCA and slag as coarse aggregate in normal concrete mixes is useful in reducing the environmental problems and also helps to maintain sustainability of the environment by reducing the new quarries. Mukharjee and Barai (2014) have addressed the effect of incorporation of colloidal Nano-Silica on the behavior of concrete containing 100% recycled coarse aggregate. Their results depicted that compressive strength, tensile strength and non-destructive parameters are enhanced due to addition of Nano-Silica. The study also revealed that the characteristics of recycled aggregate concrete resembled with that of natural aggregate concrete with the addition of little amount (3%) of Nano-Silica.

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 RCA based concrete with micro-silica as replacement to ordinary Portland cement. Prusty *et al*. (2015) have shown that Taguchi method is an efficient tool to ascertain the effect of various parameters in concrete. The w/c ratio is ranked one followed by Nano-Silica have higher influence when compared to the other two factors namely RCA (%) and maximum cement content.

Yaragal *et al*. (2016), have reported processing of recycled aggregates from C&D waste adopting 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.

1.4 Recycled fine aggregate (RFA)

The uncontrolled consumption of natural sands has led to situations of exhaustion of availability of these aggregates, with various warnings, that it is going to happen in several regions, Manasseh (2010). Resorting to crushed sands has shown to be unviable given the cost (fundamentally energy related) associated to its production as well as the fact that the shape of these particles is not the most suitable to achieve the best workability for concrete. On the other hand the extraction of sands in coastal areas brings along deterioration of the ecosystems with unpredictable long term repercussions, such as the elimination of local species and consequent unbalances.

Even though advances reached in the study of concrete using RCA have been enough to reliably say that, it is possible to make concrete with RCA with perfectly acceptable characteristics for current use, the use of RFA is still limited. One of the important areas of research currently being developed is the possibility of using RFA from C&D waste as replacement, to natural sand in concrete. This goal serves a greater environmental purpose, as it fights abiotic resources depletion, namely by reducing river banks and coastal sand extraction. Research efforts on this matter have been set aside mostly because some early attempts on the use of these materials proved to be severely detrimental to concrete's performance. The main causes for this weak performance of RFA were the low particle's density, and high water absorption capacity, that hinders the mixing.

Although the use of coarse aggregates in concrete production is an increasingly common practice, encouraged or imposed by the national authorities, the use of RFA, whatsoever their nature is still very restricted or even barred, due to the lack of consolidated knowledge in this area. Even then, the growing search for natural resources, namely stone, is creating an unsustainable environmental pressure urging the need to change the existing paradigm of not allowing the use of RFA in concrete production.

Review by De Brito and Evangelista (2015) reported that most standards and recommendations available on the use of RA in concrete limit or even forbid the use of RFA. National specifications and standards of Swiss, Japan, and Russia, allow the use up to 100% of RFA, if it is unreinforced concrete. In Brazil, one can use up to 100% of RFA as along as concrete is for non-structural purpose. In Holland, one can use up to 100% of RFA if the coarse aggregates are natural (limited to non-aggressive environments and maximum strength classes of C20/25 and C40/50 for RFA from C&D waste and concrete respectively). Germany, Hong-Kong, UK, Portugal and Spain strictly forbid the use of RFA, what-ever their nature or the concrete final application.

The typical characteristics of this material are that it is lighter and more porous than Natural Fine Aggregate (NFA). During characterization of RFA, one must bear in mind their greater porosity and there must be a unified procedure to determine their water absorption, given the scatter of existing works/proposals. The production of concrete with RFA cannot be done the same way as for conventional concrete. The presence of more porous aggregates than the traditional ones imposes that the water absorption of the RFA must be taken into account to calibrate the w/c ratios.

One of the most distinguishing characteristics between NFA and RFA is their density. The difference arises from the porous material adhered to the stone material particles (mortar, ceramics, plaster, among other) that not only decreases the density but it also increases the water retention capacity. The results from various authors range significantly, denoting a great scatter of this entity, directly linked with the nature of the recycled materials. The density values show

Table 1 Physical properties of ordinary portland cement (OPC 43 Grade)

Property	Result obtained			Requirements as per IS:4031(PART I)-1988			Remarks
Specific gravity	3.10			--			
Normal consistency	30%			--			Satisfies IS code requirements
Setting times, minutes	Initial 75 Final 280			Not less than 30 Not more than 600			
Fineness, m^2/kg	310			Not less than 300			
Soundness, mm	2.50			Not more than 10 mm			
Compressive strength, MPa	3 Days	7 Days	28 Days	3 Days	7 Days	28 Days	
	26	38	46	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	93.9	90-100	90-100	90-100	95-100	
2.36 mm	90.7	60-95	75-100	85-100	95-100	
1.18 mm	58.3	30-70	55-90	75-100	90-100	
600 μ	16.3	15-34	35-59	60-79	80-100	
300 μ	5.5	5-20	8-30	12-40	15-50	
150 μ	0.0	0-10	0-10	0-10	0-10	

Table 3 Properties of fine aggregates

Property	Result
Specific gravity	2.63
Bulk density	Loose: 1468 kg/m^3 Compact: 1652 kg/m^3
Moisture content	Nil

variations between 1.89 g/cm^3, (Levy and Helene 2007) and 2.7 g/cm^3, (Mueller and Winkler 1998). The water absorption values between 4.3%, (Mueller and Winkler 1998), and 13.1% (Evangelista and De Brito 2007), depending on the RFA's nature.

More recent studies, such as those of Evangelista and De Brito (2007, 2010) and Kou and Poon (2009), have shown that it is possible to make concrete with RFA with no significant performance loss. Therefore, in order to reverse the trend of restricting the use of RFA, it is necessary to advance research on the detailed analysis and characterization of RFA and the RFA based concrete. This study in line with above discussion reports performance and performance enhancement of RCA based concrete. It also examines the performance of RFA in mortar and in concrete.

2. Materials

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	96.1	85-100	95-100	
10 mm	4.2	0-20	25-55	
4.75 mm	0	0-5	0-10	

Table 5 Properties of coarse aggregates

Property	Result
Specific gravity	2.71
Bulk density	Loose: 1354 kg/m^3 Compact: 1508 kg/m^3
Moisture content	Nil

Table 6 Properties of recycled coarse aggregates

Property	Results
Specific gravity	2.56
Water absorption	2.7%
Fineness modulus	6.83

Table 7 Sieve analysis results of natural and recycled coarse aggregates

Sieve size	% Finer	
	NCA	RCA
20 mm	100	100
16 mm	67.3	70.1
12.5 mm	31.0	27.2
10 mm	0.7	0.5

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

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. 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. The average 28 day compressive strength of concrete was about 20 MPa.

Table 6 shows the properties of recycled coarse aggregate. Sieve analysis results of natural and

Table 8 Sieve analysis fine aggregates

Sieve size	% Finer		
	NFA	RFA	IOT
4.75 mm	93.9	95.0	92.5
2.36 mm	90.7	92.5	83.6
1.18 mm	58.3	65.0	68.5
600 μ	16.3	22.3	33.2
300 μ	5.5	8.6	10.3
150 μ	0.0	2.0	0.2

Table 9 Properties of recycled fine aggregates (without blending i.e., either IOT/natural fractions)

Property	Results
Specific gravity	2.6
Water absorption	6.5%

recycled coarse aggregates are presented in Table 7.

Table 8 presents sieve analysis results for RFA compared to NFA. Table 9 shows specific gravity and water absorption results for RFA. As regards to the use of RFA, two types of hybrid FA, are attempted. Nearly 20% of the material in river sand (control) is finer than 600μ. River sand based RFA, meant in this study is RFA fractions taken exactly same as river sand up to 1.18 mm passing and mixed with proportionate river sand fractions for 600μ, 300μ, and 150μ. Iron ore tailings based RFA, meant RFA fractions taken exactly same as river sand up to 1.18 mm passing and mixed with proportionate iron ore tailings fractions for 600μ, 300μ, and 150μ.

2.2 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. Potable quality water is used.

2.3 Iron ore tailings (IOT)

Mining industries produce one of the waste materials called mine tailings. The source of IOT here being tailing dam located in Kudremukha, Karnataka, India. IOT which is used as a replacement material to river sand satisfied codal requirements of gradation confirming to Zone I of IS: 383-1970.

2.4 Silica fume

Silica fume used in this study belongs to CORNICHE SF brand. It is compatible with any of the high range water reducing admixture to provide added workability with low w/c ratios.

2.5 Mix adopted

Table 10 Test matrix required for compressive strength performance and strength enhancement studies

RCA (%)	Concrete cubes							
	For performance	For performance enhancement (slurry treated RCA)						
	OPC based	OPC, RCA cement slurry treated	85% OPC & 15% SF based		70% OPC & 30% FA based		30% OPC & 70% GGBS based	
			28d	56d	28d	56d	28d	56d
0	3	3	3	3	3	3	3	3
25	3	3	-	-	-	-	-	-
50	3	3	3	3	3	3	3	3
75	3	3	-	-	-	-	-	-
100	3	3	3	3	3	3	3	3
Total	15	15	09	09	09	09	09	09

Table 11 Mix proportion per cubic meter for OPC based concrete

RCA (%)	C (kg)	FA (kg)	CA (kg)	RCA (kg)	W (kg)
0	400	600	1200	-	200
25	400	600	900	300	200
50	400	600	600	600	200
75	400	600	300	900	200
100	400	600	0	1200	200

Table 12 Chemical admixture dosages for various compositions at different levels of RCA

RCA %	OPC based (ml/kg)	OPC, RCA cement slurry treated (ml/kg)	85% OPC & 15% SF based (ml/kg)	70% OPC & 30% FA based (ml/kg)	30% OPC & 70% GGBS based (ml/kg)
0	0	0	8	0	0
25	0	0	-	-	-
50	0	0	9	0	6
75	0	4	-	-	-
100	0	8	12	0	6

Nominal mix 1:1.5:3 and w/c=0.50, is adopted. The concrete was mixed in a concrete mixer and poured into cube moulds of size 150 mm. They were given adequate vibration to achieve required compaction. The cubes were de-moulded after 24 hours and cured for 28 days in water. Cubes were air dried before crushing them to generate C&D waste from which RCA and RFA shall be extracted as explained in sections 3.1 and 3.4 respectively.

Concrete using cement slurry coated RCA with the same mix proportion of 1:1.5:3, w/c=0.5, was produced to study the performance enhancement of RCA based concrete. Mixing, placing, demoulding and curing conditions followed are the same as discussed above.

Concrete blended with fly ash with the same mix proportion and same w/c ratio was produced to study the performance enhancement. 30% of cement was replaced with fly ash. Mixing, placing, demoulding and curing followed are the same as discussed.

Concrete blended with GGBFS was produced the same way, to study the performance enhancement. 70% of cement was replaced with GGBFS. Mixing, placing, demoulding and curing conditions adopted being the same.

3. Experimental methodology

3.1 Methodology for obtaining recycled coarse aggregate

To cast 100 no's of cubes of 150 mm, a nominal mix (1:1.5:3), was adopted to produce construction and demolition waste. After 28 days water curing, the specimen were crushed to failure using compression testing machine and the broken concrete is re-processed for recycling into RCA based concrete, using Los Angele's machine, the output was sieved, washed and sun dried before using it as RCA.

Test cubes of 150 mm RCA based concrete were cast for nominal mix proportion of 1:1.5:3, with w/c=0.5. The recycled aggregates were all water soaked for 24 hours before being used, except the cement slurry coated case, wherein soaking in cement slurry was done for 24 hours.

3.2 Mixing method

As the water absorption of RCA being high it is more likely to absorb the water which is added to the concrete for cement hydration purpose. This will lead to less effective w/c ratio and less workability. Adding water to compensate for the absorption will also create problems as the effective w/c ratio will be very high and it will give high workability. Moreover the concrete will not be in a uniform condition as the mortar paste will be much dilute and chances of bleeding will be high. Hence the RCA was soaked for 24 hours in water prior to mixing. The RCA was taken out after 24 hours of soaking and allowed for air drying of 30 minutes before using. This prevented further absorption of water by the RCA.

3.3 Slump tests

Initial experiments were conducted to get a slump of at least 75-100 mm without super plasticizers. Standard slump cone apparatus is used for measuring the value of slump. Table 10 shows a test matrix for compressive strength performance and enhancement.

The mix proportion details of the OPC based concrete are given in Table 11. The water cement ratio was taken as 0.5. Mixes were with 0%, 25%, 50%, 75%, and 100% RCA replacing NCA by weight.

Similar test matrix were used for other four performance enhancement techniques attempted. However the dosage of chemical admixture (CONPLAST SP 430) has been suitably used to give workability slump range of 75-100 mm. The details of chemical admixture dosages for various compositions are presented in Table 12.

3.4 Methodology for obtaining recycled fine aggregate

The same material from which RCA has been extracted, is then passed through 4.75 mm sieve, and is washed and sun dried. The fractions finer than 600μ are removed for the reason explained earlier, but substituted with either river sand or IOT fractions, in their place in same quantities as in NFA, to perform as RFA.

Table 13 Test matrix for compressive strength of mortar cube

Fine aggregate	3 Day	7 Day	28 Day
All River sand	3	3	3
RFA and River sand fines	3	3	3
RFA and IOT fines	3	3	3

Table 14 Test matrix for compressive strength of concrete cubes

Fine aggregate adopted	28 Day
All River sand	3
RFA and River sand fines	3
RFA and IOT fines	3

Fig. 1 Natural and recycled coarse aggregates

To overcome this problem, which brings down the performance of mortar, as correct water absorption cannot be accounted for these fine fractions. Experiments were planned to study the performance using two alternative hybrid fine aggregates developed namely RFA based river sand (consisting solely of RFA fractions, along with required proportion of 600μ, 300μ and 150μ fractions from river sand) and RFA based iron ore tailings (consisting solely of RFA fractions, along with required proportion of 600μ, 300μ and 150μ fractions from iron ore tailings).

RFA mortar cubes (50 cm^2) with proportion of 1:3, were cast. The RFA here is meant RFA with either river sand blended or RFA with IOT blended.

Experiments were planned to test the compressive strength of River sand, RFA based river sand and RFA based IOT, mortar cubes for 3, 7, and 28 days of curing. Table 13 shows the test matrix for studying the compressive strength of different mortar compositions.

Further to study the performance of using RFA in concrete, 150 mm concrete cubes 1:1.5:3.0,

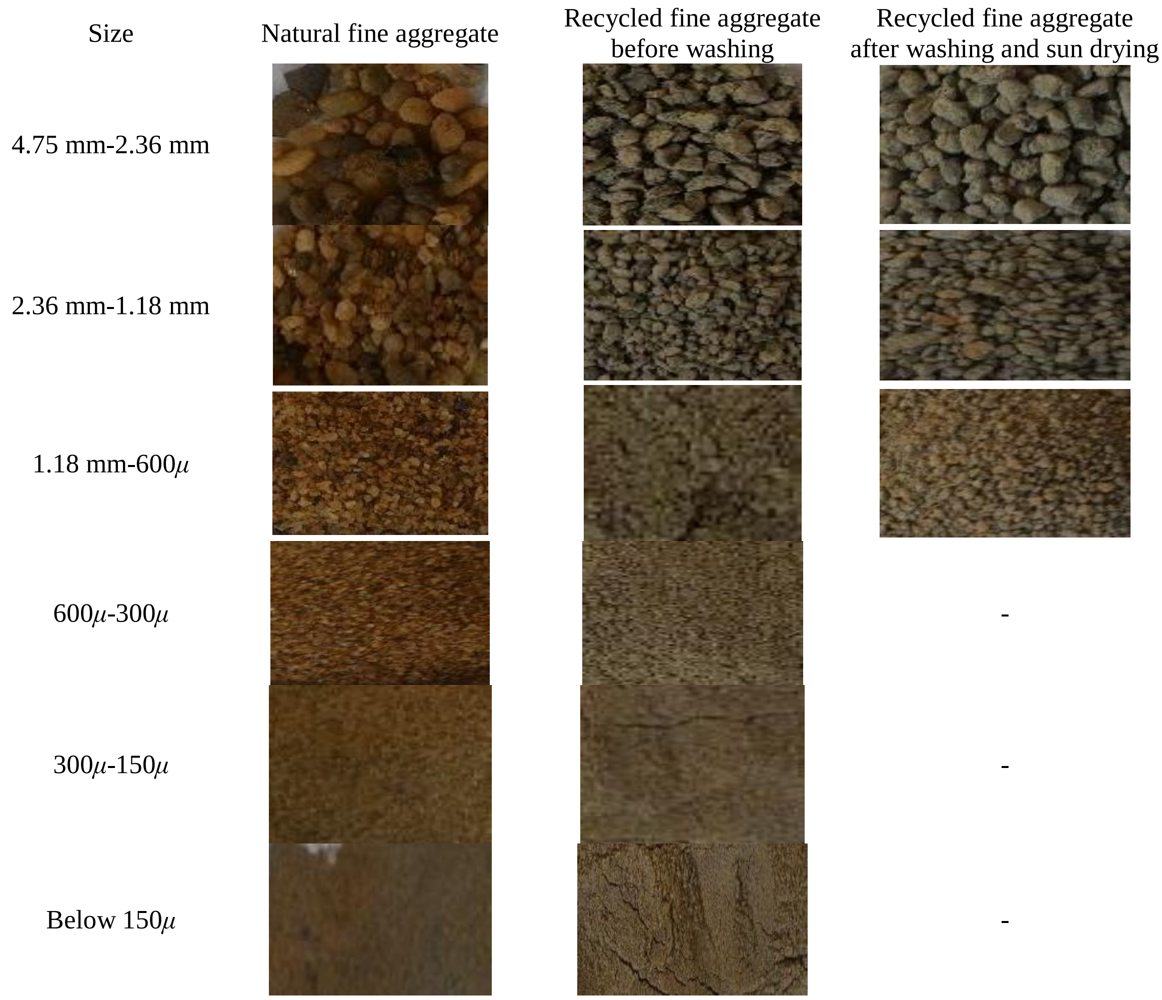

Fig. 2 Natural and recycled fine aggregates

w/c=0.50, were cast with three verities of fine aggregates to the tune of 100%. Experiments were planned to test the compressive strength of River sand, RFA based river sand and RFA based IOT, based concrete cubes for 28 days of curing in water. Table 14 shows the test matrix for testing compressive strength of concrete.

3.5 Compressive strength

The strength measured in concrete depends on some factors including the age, degree of hydration, rate of loading, method of testing, specimen geometry, and the properties and proportions of the constituent materials. Mostly, concrete strength improves with the increase of age.

The concrete samples with RCA are tested for 28 days strengths in the case of OPC and 28 days and 56 days strengths in the case of SF, FA and GGBS blended concretes. The testing of the cubes was done using a 2000 kN capacity compression testing machine.

Table 15 Slump results for OPC based concrete and for other performance enhancement techniques

RCA (%)	Slump (mm)				
	OPC based	Cement slurry coated	SF based	FA based	GGBS based
0	95	98	95	100	98
25	90	92	-	-	-
50	88	88	85	95	85
75	85	90	-	-	-
100	80	88	78	85	82

4. Results and discussion

In this section, the results of tests performed on RCA based concrete are discussed. The workability of fresh concrete and the variation in compressive strength are discussed in detail. Several performance enhancement techniques have been attempted to achieve the strength of RCA based concrete to be equal to or more than the strength of no recycled aggregate based concrete. In addition efforts have been made to exclusively check the performance of using RFA in cement mortar and cement concrete.

4.1 Physical appearance of natural and characterized recycled coarse aggregates

Fig. 1 presents photographs of natural and RCA, for three size ranges. The quality of processed recycled coarse aggregates appears to be good by visual observations.

4.2 Physical appearance of natural and characterized recycled fine aggregates

Fig. 2 presents photographs of natural fine aggregates, recycled fine aggregates before washing and RFA after washing and sun-drying, for various size ranges. During washing all sizes smaller than 600μ were not collected, as they were too fine and water absorption quantification was involved and not accurately assessable.

4.3 Fresh concrete workability tests

Initial experiments were conducted to obtain a slump in the range 75-100 mm without super plasticizers. Standard slump cone apparatus was used for measuring slump. During the slump tests it was found that the workability of fresh concrete made with 100% replacement of RCA had slump value close to zero mm. With increase in percentage of RCA in concrete the workability was getting lower and lower. This was due to the higher water absorption (2.7%) of the RCA as compared to the natural coarse aggregate (0.5%). Adding water to compensate for this absorption was not a good option as exact amount could not be ascertained. So it was decided to soak RCA for 24 hours before use, so that it does not absorb water during the process of mixing. The slump results obtained for OPC based concrete and for other concretes where performance enhancement techniques were attempted are presented in Table 15.

4.4 Usage potential of recycled coarse aggregates

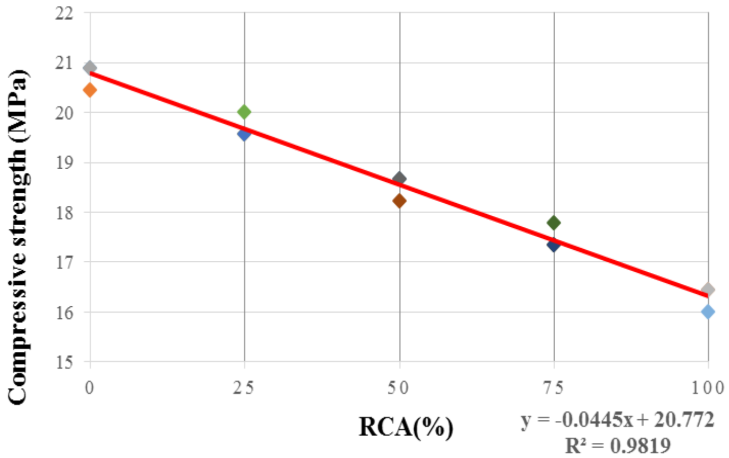

Fig. 3 Compressive strength (MPa) variation with RCA for OPC based mixes

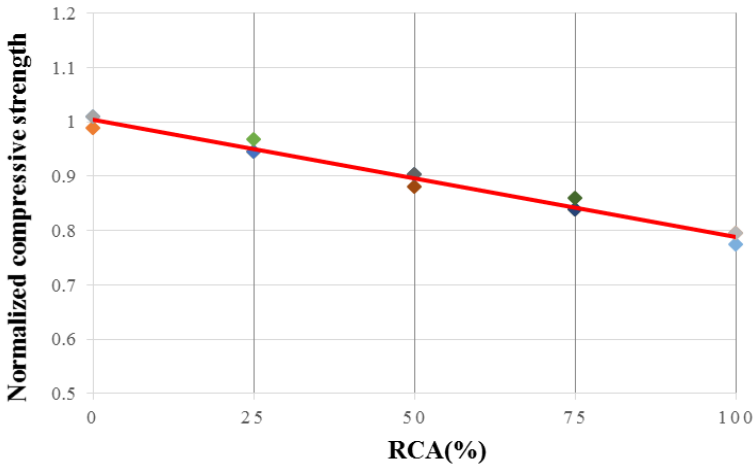

Fig. 4 Normalized compressive strength variation with RCA for OPC based mixes

4.4.1 Performance of RCA based concrete

RCA adopted was 24 hours water soaked before use in producing concrete. The results of the compressive tests for OPC based concrete mixes are presented in Figs. 3 and 4, in absolute and normalized values respectively. The compressive strength is observed to decrease with increase in percentage of RCA replacement. The compressive strength being 21.0 MPa for the control mix and it decreases to 16.3 MPa for 100% RCA based concrete. This decrease is attributed to the lesser bond between the RCA and the new mortar.

4.4.2 Performance enhancement studies on RCA based concrete

As discussed in previous section 4.4.1, nearly 20% decrease in strength is observed for 100% RCA based concrete. Attempts were made to achieve strengths of 100% RCA based concrete either equal to or more than that for the case of 0% RCA based concrete, with the following four approaches,

(i) Use of cement slurry coated RCA (ii) 15% OPC replacement by Silica Fume (iii) 30% OPC replacement by Fly Ash (iv) 70% OPC replacement by GGBS

Use of cement slurry coated RCA

Preliminary studies were under taken to surface treat, RCA adopting cement slurry, Fly Ash slurry, and GGBS slurry. By surface treatment, the voids in the Inter Transition Zone (ITZ) gets filled up to some extent making the RCA more denser. Both cement slurry and GGBS slurry were found suitable on RCA treated for 24 hours immersion, showed an increase of weight by about 8-9%. However fly ash slurry treatment showed an increase of only about 1.2%. Experiments were planned to study the performance enhancement of cement slurry treated RCA based concrete. The results are as shown in Fig. 5.

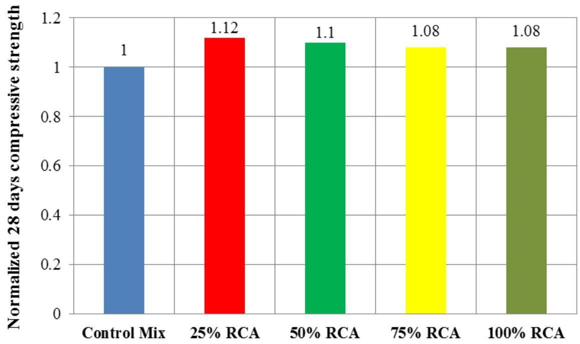

Fig. 5 Compressive strength results for cement slurry treated RCA based concrete

It is clear from Fig. 5, that this method of RCA treatment is very effective as strength achieved for RCA based concrete is equal to or more than that for no RCA based concrete or Normal Aggregate Concrete (NAC), for all levels of RCA replacement.

Adopting 15% OPC replacement by silica fume

Fig. 6 presents the results of both 28 days and 56 days strength variation of silica fume blended concretes. It is clearly seen that for both levels of RCA usage i.e., 50% and 100% replacement to NCA, the obtained 56 days strength is higher than that for NCA based concrete.

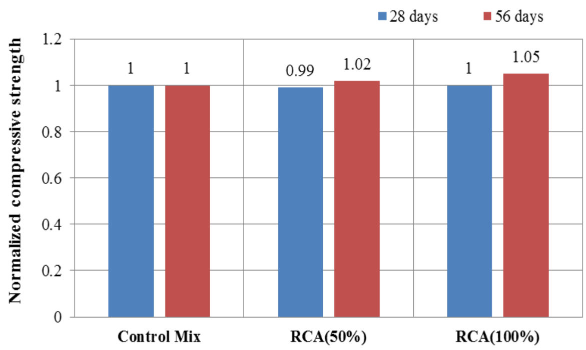

Fig. 6 Normalized compressive strength results for silica fume blended RCA based concrete

Adopting 30% OPC replacement by fly ash

Fig. 7 presents the results of both 28 days and 56 days strength variation of fly ash blended concretes. It is clearly seen that for both levels of RCA usage i.e., 50% and 100% replacement to NCA, the obtained 56 days strength is higher than that for NCA based concrete.

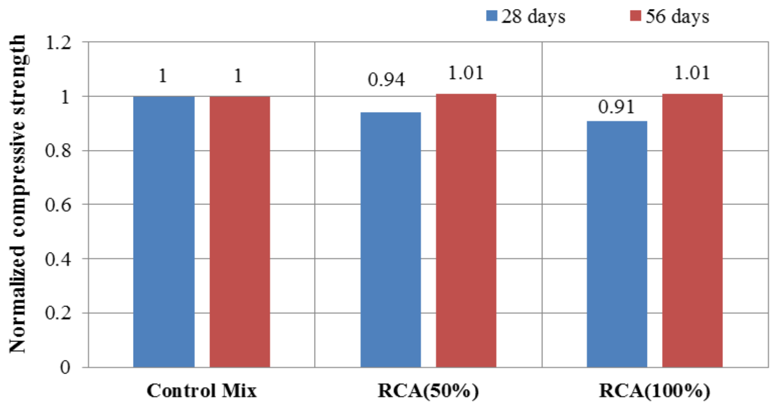

Fig. 7 Normalized compressive strength results for fly ash blended RCA based concrete

Adopting 70% OPC replacement by GGBS

Fig. 8 presents the results of both 28 days and 56 days strength variation of GGBS blended concretes. It is clearly seen that for both levels of RCA usage i.e., 50% and 100% replacement to NCA, the obtained 56 days strength is higher than that for NCA based concrete.

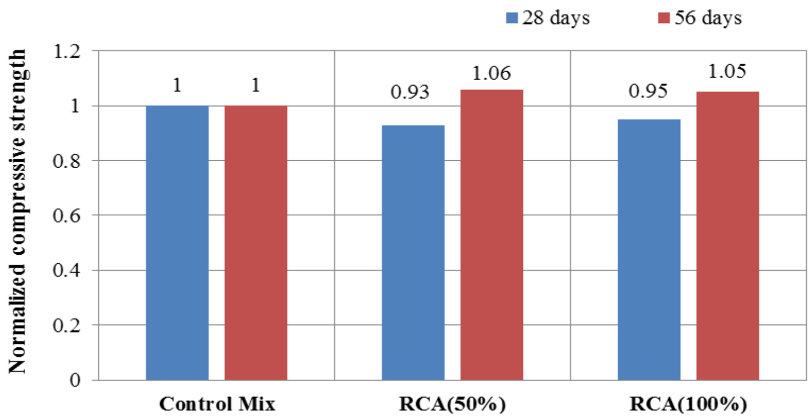

Fig. 8 Normalized compressive strength results for GGBS blended RCA based concrete

4.4.3 Usage potential of recycled fine aggregate (RFA)

Performance of RFA in cement mortar

Preliminary studies on gradation and water absorption of various particle size range for fine aggregates requirements indicated that the RFA constituents of sizes finer than 600μ, 300μ and 150μ were behaving like clay and forming lumps, when in contact with water. It was difficult to determine exactly the water absorption of these three particle fractions.

The 3, 7, and 28 days strength results of mortar cubes consisting of, (i) River sand alone as reference or control, (ii) RFA based river sand, and (iii) RFA based iron ore tailings is presented in Table 16 and Figs. 9 and 10.

Figs. 9 and 10, clearly shows the superior performance of both RFA based river sand, and RFA based iron ore tailings, as hybrid fine aggregates, when compared to the case of all, river sand, for all the three curing periods considered in the study. At 28 days RFA+RS based fine aggregate, has shown an enhanced strength of 8% and it is 35%, when RFA+IOT based fine aggregate is used.

The results clearly confirm the potential use of RFA based river sand and RFA based IOT as substitute to the very scarce and fast depleting natural river sand. This study recommends RFA based IOT, as a viable replacement to natural river sand, for use in mortars. These results indicate an optimal utilization of about 80% RFA in cement mortars.

Table 16 Compressive strength results of mortar using two blends of hybrid RFA and all river sand

Fine aggregate	3 Day (N/mm^2)		7 Day (N/mm^2)		28Day (N/mm^2)	
	16.0		22.0		24.0	
All River sand	22.0	19.3	26.0	22.3	26.0	24.7
	20.0		20.0		24.0	
	20.0		24.0		28.0	
RFA and River sand fines	20.0	19.3	22.0	24.0	26.0	26.7
	18.0		26.0		26.0	
	22.0		30.0		34.0	
RFA and IOT fines	23.0	22.7	30.0	29.3	34.0	33.3
	23.0		28.0		32.0	

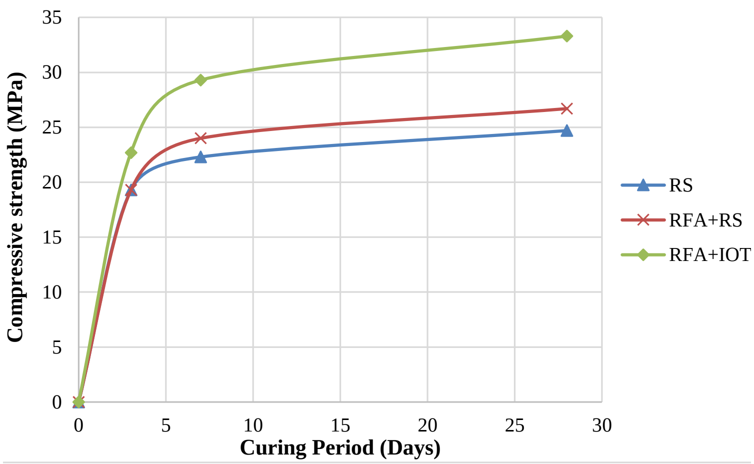

Fig. 9 Average compressive strength variation of different mortar compositions

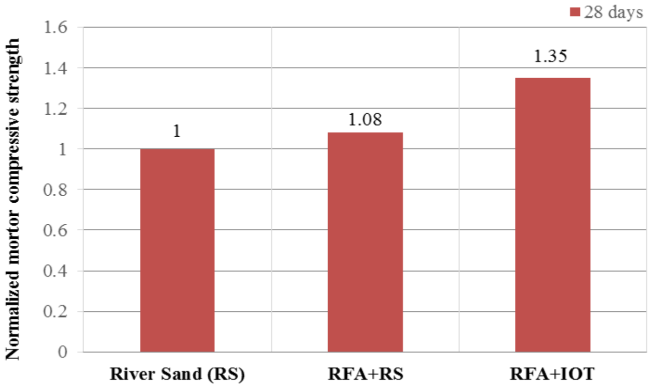

Fig. 10 Normalized mortar compressive strength for different mortar compositions

Table 17 Compressive strength results of different fine aggregates based concrete

Fine aggregate	Weight of cubes (kg)	Failure load (kN)	Compressive strength (N/mm^2)	Average compressive strength (N/mm^2)
All River sand	8.358	660	29.3	28.9
	8.285	650	28.9	
	8.305	640	28.4	
RFA and River sand fines	8.288	660	29.3	30.2
	8.365	680	30.2	
	8.295	700	31.1	
RFA and IOT fines	8.296	690	30.7	31.1
	8.306	710	31.6	
	8.368	700	31.1	

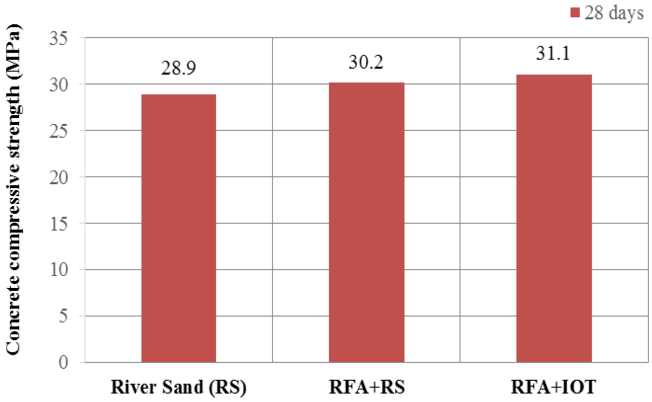

Fig. 11 Compressive strength (MPa) variation of different fine aggregates based concrete

Performance of RFA in cement concrete

Table 17 and Figs. 11 and 12, presents the 28 days compressive strength results of concrete

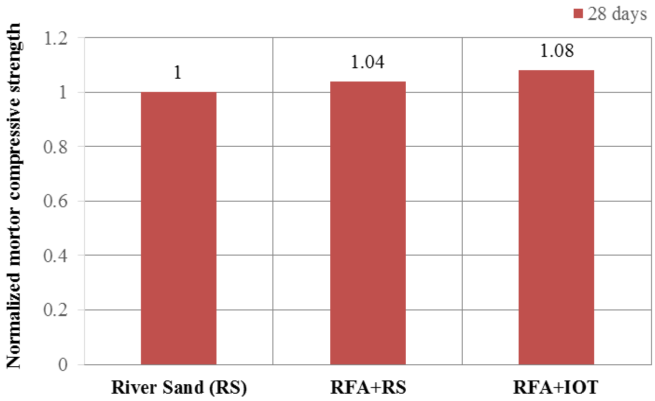

Fig. 12 Normalized compressive strength variation of different fine aggregates based concrete

using RS, RFA+RS, and RFA+IOT as fine aggregates. As in mortar, the concrete also shows enhanced strength performance for both RFA based RS, and RFA based IOT, as against control concrete having all river sand. RFA+RS based fine aggregate, has shown enhanced strength of 5% and it is 8% for the case of RFA+IOT based fine aggregate. The study recommends RFA based IOT as a viable replacement to natural river sand for use in concretes.

5. Conclusions

• As the degree of processing gets better and better the RA tends to be closer to NA. Hence RA after processing shows better results than unprocessed RA.

• The extent of water absorption of recycled aggregate decides the strength of RCA based concrete.

• A maximum reduction of about 21% was noticed in compressive strength for full replacement of natural coarse aggregates by RCA.

• The four methods adopted to enhance performance of RCA based concrete have given favorable result, so as to utilize 100% RCA in place of NCA, in concrete. For the cases of blended concrete with SF, FA, and GGBS, curing period of 56 days is a must.

• RFA can effectively be used (up to 100% replacement to river sand) in mortar and concrete as fine aggregate with little modification (blending partly either with river sand or IOT, for fractions finer than 600μ), without loss in performance.

• This study has been a successful attempt, suggesting some viable techniques to march towards green infrastructure and sustainable construction.

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