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Strength Performance of Concrete incorporating Coarse Recycled Aggregate

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Abstract: *This paper presents the influence of different amounts of recycled coarse aggregate (RCA) obtained from a demolished reinforced concrete (RC) building near Bhubaneswar region, about 15-20 years old, on the strength performance of concrete. To analyze the behavior of concrete, RCA with replacement of 10%, 20%, 30%, 40%, 50% are used in M30 grade concrete mix. The mix proportion used in this study was 1:1.15:2.73 with w/c is 0.40. The mix proportions are prepared with two types of cements i.e. Ordinary Portland Cement (OPC) and Portland Pozzolana Cement (PPC). The properties namely compressive strength, flexural strength and split tensile strength are studied after the curing period of 7, 28 and 90 days. From the experimental result it is observed that there is very slight difference in the compressive strength, flexural strength and split tensile strength of concrete upto 20% replacement of RCA and there was a noticeable reduction in workability with the increase in replacement ratio. The test results also indicate that the early age compressive strength is higher for concrete made with OPC and RCA and later age strength is higher for PPC and RCA.*

Keywords: *Recycled coarse aggregates (RCA), compressive strength, flexural strength, split tensile strength, workability*

1. Introduction

The concept of sustainable concrete in construction field has been gaining popularity at the present time. To achieve more sustainability of construction is by conserving new raw materials such as natural aggregates and reusing construction and industrial wastes. Recycled concrete aggregate is a common construction waste that is produced from demolished concrete structures as they approach the end of their service life. Now a day's sustainable engineering approach is also plays a major role in mix design of concrete. This requires several elements; maximizing concrete durability, conservation of materials, use of wastes and supplementary cementing materials. These materials can improve the concrete durability, reduce the risk of thermal cracking in mass concrete and are less energy and CO_2 intensive than cement. Use of aggregates obtained from crushed concrete is an example of recycling and conservation of raw materials.

Recycling is the act of processing the used material for use in creating new product. The usage of natural aggregate is getting more and more intense with the advanced development in infrastructure area. In order to reduce the usage of natural aggregate (NA), recycled aggregate (RA) can be used as the replacement materials. Recycled aggregate are comprised of crushed, graded inorganic particles processed from the materials that have been used in the constructions and demolition debris. These materials are generally obtained from buildings, roads, bridges, and sometimes even from catastrophes, such as wars and earthquakes. There are few definitions given to recycled aggregate by various authors. The crushed concrete, after separation from other construction and demolition waste is sieved can be used as a substitute for natural coarse aggregate (NCA) in concrete or as sub-base or a base layer in pavements. This type of recycled material is called recycled aggregate Poon et al. (1). In general "The recycled aggregate can be defined as a coarse or fine aggregate which is obtained after sieving and separating from other constituent of construction and demolition waste and graded as per requirement". The applications of RA in the construction areas are wide and have been used since long time. The applications are different from country to country. Recycled aggregate have been used as concrete kerb and gutter mix in Australia and paving blocks in Hong Kong. Also recycled aggregate are used as granular base course in the road construction, embankment fill, backfill materials and building blocks.

Experimental as well as theoretical studies on use and properties of RA have been contributed by the several researchers. The brief literature reviews of these studies are as follows: Topcu and Guncan (2) investigated on using waste concrete as aggregate. In their study, various mechanical properties of concretes were examined. These concretes were obtained with the addition of C 16 (28-day compressive strength of 16 Mpa) pieces as aggregate in weight percentages of 0, 30, 50, 70 and 100%. Olorunsogo and Padayachee (3) investigated on performance of recycled aggregate concrete (RAC) monitored by durability index for which durability indexes, such as chloride conductivity, oxygen

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permeability and water absorptivity, of three different concrete mixes containing 0%, 50% and 100% RA were monitored at ages 3, 7, 28 and 56 days. The results showed that durability quality reduced with increase in the quantities of RA included in a mix. However, as expected, the quality improved with the age of curing.

Poon et al. (1) studied the use of RA in molded concrete bricks and blocks. For this, laboratory trials were conducted to investigate the possibility of using RA from different sources in Hong Kong, as the replacement of both coarse and fine natural aggregates in molded bricks and blocks. Zaharieva et al. (4) compared the water permeability, air permeability and surface permeability of RAC with those of a control concrete made with natural aggregate. The study shows that the permeation properties of RAC depend on mix-design, conditions of curing and drying of samples. Relationships between permeability and other physical characteristics of concrete such as water absorption capacity and diffusivity were discussed. Katz (5) conducted an experimental investigation on properties of concrete made with RA from partially hydrated old concrete, for which concrete having a 28-day compressive strength of 28 Mpa was crushed at ages 1, 3 and 28 days to serve as a source of aggregate for new concretes, simulating the situation prevailing in precast concrete plants. Chen et al. (6) studied on building rubbles as recycled aggregates. For this, a series of experiments using RA of various compositions from building rubble were conducted. Poon et al. (7) investigated the influence of moisture states of natural and recycled aggregates on the properties of fresh and hardened concretes. The results suggested that an air dried aggregate that contains not more than 50% RA is optimum for producing normal strength RAC.

Topcu and Sengel (8) investigated on properties of concretes produced with waste concrete aggregate (WCA). In this study, the physical and mechanical properties along with their freeze-thaw durability of concrete produced with WCAs were investigated. Zaharieva et al. (9) conducted a study that deals with concrete containing building waste recycled as aggregates. The frost resistance is used as a durability indicator. The characteristics of RA and their impact on the characteristics of RAC are presented. Xiao et al. (10) investigated the compressive strength and the stress-strain curve of RAC with different replacement percentages of RCA. Khatib (11) carried out an investigation on properties of concrete incorporating fine recycled aggregate, in which the fine aggregates were replaced by crushed concrete and crushed brick. Tam et al. (12) attempted to examine the problems of recycling old concrete by investigating the microstructure and phase transformation of the concrete samples collected from buildings with 46 and 37 years of services. Xiao et al. (13) conducted an experimental study on the seismic performance of frame structures with RAC. Eguchi et al. (14) developed a production method for recycled concrete that is different from that of the draft. The RCA is produced by a simple assembled system of equipment, and is mixed with ordinary coarse aggregate to ensure the quality required of structural concrete.

Tam et al. (15) proposed a two-stage mixing approach for improving the strength of RAC, by testing mixes with upto 30% RA replacement. They explored RA substitution ranging from 0% to 100% and compared their performance with the traditional mixing procedure. Xiao and Falkner (16) carried out thirty six pullout test in order to investigate bond behaviour between RAC and steel rebars. Three RCA replacement percentages (i.e., 0%, 50% and 100%) and two types of steel rebar (i.e., plain and deformed) were used. Based on the test results, the influences of both RCA replacement percentages and the rebar surface on the bond strength between the RAC and steel rebars were investigated. Etxeberria et al. (17) produced four different RAC, made with 0%, 25%, 50% and 100% of RCA, respectively. The mix proportions of the four concretes were designed in order to achieve the same compressive strengths. Rahal (18) presented the results of an experimental study on some of the mechanical properties of RAC as compared to those of the conventional normal aggregate concrete (NAC). Ten mixes of concrete with target compressive cube strength ranging from 20 to 50 MPa were cast using NCA and RCA. Poon and Chang (19) presented a study on the properties of concrete having blocks prepared with recycled concrete aggregates that are contaminated by materials (tiles, clay bricks, glass, wood) commonly found in the construction and demolition waste. The density, compressive strength, split tensile strength, water absorption value, abrasion resistance, skid resistance and some durability parameters were measured.

Casuccio et al. (20) studied the failure mechanism of RAC of three series of concretes with different compressive strength levels. Poon and Lam (21) were evaluated on the effect of aggregate-to-cement ratio and types of aggregates on the properties of pre-cast concrete blocks. Tangchirapat et al. (22) used ground rice husk-bark ash (RHBA) as a pozzolanic material in concrete containing high amount of RA. The concretes were prepared by using 100% of RCA, then river sand was replaced by recycled fine aggregate (RFA) at 0%, 50%, and 100% by weight of the fine aggregate. Corinaldesi and Moriconi (23) manufactured concrete specimens by completely replacing fine and coarse aggregates with RA from a rubble recycling plant. Corinaldesi and Moriconi (24) evaluated both mechanical and rheological behavior of cementitious mortars prepared with three different kinds of RA: one is made of concrete scraps obtained as rejected material from precast concrete production, one is based on recycled bricks and the last one is from a recycling plant in which demolition waste is suitably treated. Debieb et al. (25) studied on roller compacted concrete with contaminated RA. Padmini et al. (26) studied the properties of recycled aggregates derived from parent concrete (PC) of three strengths, each of them made with three maximum sizes of aggregates. Tabsh and Abdelfatah (27) investigated the strength of concrete made with recycled concrete coarse aggregate. The variables that are considered in the study include the source of the recycled concrete and target concrete strength. Poon and Kou (28) presented a study on properties of concrete prepared with PVA-impregnated recycled concrete aggregates in which they tried to improve the properties of recycled concrete aggregates by their impregnation with polyvinyl alcohol (PVA). Corinaldesi (29) investigated the mechanical and elastic behavior of concretes made of recycled-concrete coarse aggregates. Cabral et al. (30) carried out a study by varying water/cement ratio and substitution of natural aggregates by recycled aggregates. Courard et al. (31) conducted a study on use of concrete road RA for Roller Compacted Concrete. Evangelista and de Brito (32) studied the durability performance of concrete made with recycled fine concrete aggregates. Abukersh and Fairfield (33) conducted a study on RAC produced with red granite dust as a partial cement replacement, for which red granite dust arising from the rock-crushing process was assessed for suitability as a replacement for upto 30% by mass of the cement content of structural grade concretes made with RCA. Corinaldesi et al. (34) prepared a RAC by replacing 30% recycled concrete aggregate coming from an industrial crushing plant in which concrete from building demolition which is suitably treated. Rao et al. (35) presented the experimental results of RAC beams prepared with different amount of recycled coarse aggregate (RCA) subjected to low velocity impact. Agrela et al. (36) presented a study on the physical and chemical characteristics of mixed recycled aggregates which have been obtained from different CDW treatment plants of Spain. Kou et al. (37) presented the results of a laboratory study on the performance of natural and recycled aggregate concrete prepared with the incorporation of different mineral admixtures including silica fumes (SF), metakaolin (MK), fly ash (FA) and Ground granulated blast slag (GGBS). The compressive and splitting tensile strength, drying shrinkage, chloride ion penetration and ultrasonic pulse velocity (UPV) of the concrete mixtures were determined.

Fonseca et al. (38) investigated on the influence of curing conditions on the mechanical performance of concrete made with recycled concrete waste, from which they showed the main results of experiments to determine the influence of different curing conditions on the mechanical performance of concrete made with coarse recycled aggregate from crushed concrete. Butler et al. (39) conducted a study on the effect of recycled concrete aggregate properties on the bond strength between RCA concrete and steel reinforcement, in which two sources of RCA were used along with one natural aggregate source. Pereira et al. (40) conducted a study on the effect of super plasticizers on the workability and compressive strength of concrete made with fine recycled concrete aggregates, in which they tried to limit the disadvantages associated with the performance of concrete containing fine recycled concrete aggregates through the use of super plasticizers. Somna et al. (41) proposed that bagasse ash, which is a large disposal landfill waste from sugar mill industries, is utilized as a pozzolanic material to improve the mechanical properties and durability of recycled aggregate concrete. Kou et al. (42) conducted a study in which, fresh concrete waste (FCW) was crushed into coarse aggregate, and then it was used to replace natural coarse granite at percentages of 0%, 15%, 30% and 50%, in producing new concrete mixes. The concrete were produced with water/cement ratios of 0.35 and 0.50. Limbachiya et al. (43) studied the use of RCA in fly-ash concrete. Mas et al. (44) presented the results of an experimental investigation on the influence of replacing natural aggregate with mixed recycled aggregate (MRA) in the mix design of non-structural concrete. Xiao et al. (45) studied the shear transfer across a crack in RAC for which 32 pre-cracked RAC push-off specimens made from 10 mix designs were tested to study the shear transfer performance across the cracks. Xiao et al. (46) proposed a model to describe the effect of recycled aggregate (RA) on the chloride diffusion in RAC. Limbachiya et al. (47) studied the use of recycled concrete aggregate in fly-ash concrete. The approach taken by them included a large substitution of natural coarse aggregates (NCA) by recycled concrete aggregates (RCA) obtained from crushed concrete debris, as well as the use of 30% fly ash (FA) as a partial substitute of Portland cement for FA concrete production. They studied the effect of both partial and full replacement of natural coarse aggregates by coarse RCA in a fly ash concrete.

The present paper focuses on detailed review of the existing works relevant to recycled aggregates and also the experimental investigation carried out on strength performance of recycled coarse aggregate concrete made with two types of cement i.e. OPC and PPC.

2. Experimental program

The experimental programme is divided into two stages. In the first stage, all these materials such as cement (OPC 43 grade and PPC), Fine aggregate (sand), natural coarse aggregate (NCA) and recycled coarse aggregate (RCA) are tested in the laboratory to establish the physical and mechanical properties of the materials. All the materials are tested as per the specification of Indian Standards. Mix design is carried out for M30 grade concrete as per the recommended guidelines for concrete mix design IS: 10262-1982 (48), and Hand Book on Concrete Mixes SP: 23-1982 (49). Various properties of the materials like crushing value, impact value and abrasion value of aggregates are tested. In the second stage, concrete specimens with two types of cement (OPC and PPC) such as cubes, cylinders and prisms are tested to know the compressive strength, flexural and split tensile strength of concrete with various recycled aggregate replacement ratio.

2.1 Materials used and properties

The cement used for the present work is OPC 43 grade and PPC. The Physical properties of cement specified by IS 8112:1989 (50) for OPC 43 grade and IS 1489 (Part 1):1991 (51) for PPC and also the value obtained experimentally are presented in Table 1.

Table 1: *Physical properties of cement*

Characteristics	Value obtained experimentally (OPC)	Value obtained experimentally (PPC)	Value specified by IS 8112:1989 (OPC-43 grade)	Value specified by IS 1489 (Part 1):1991 (PPC)
Normal consistency (%)	34	33.5	NA	NA
Fineness (m^2/Kg)	318	381	225 (min)	300 (min)
Initial setting time (mins)	115	28	30 (min)	30 (min)
Final setting time (mins)	240	450	600 (max)	600 (max)
Specific gravity	3.12	3.10	3.15	3.00
Compressive strength, MPa				
At 3 days	28	16.4	23 (min)	16 (min)
At 7 days	40	25.60	33 (min)	22 (min)
At 28 days	49	38.20	43 (min)	33 (min)

The sand was supplied from ‘Trisulia’, situated on the river base of ‘Kathajodi’ and its tributary ‘Kuakhia’. Sand is used as fine aggregate which is passing through IS 4.75 mm sieve. NCA was supplied by the crusher at Tapanga, near Khurda. The size of aggregates was between 10 mm and 20 mm. RCA used in this project was brought from Krishna Nagar which is situated between Bhubaneswar and Khurda. The source of the aggregates was a demolished building of about 15 years old. The aggregates were separated by crushing the demolished debris and were then cleaned. The aggregates of size between 10 mm and 20 mm were used for casting. The location or source of recycled aggregate is shown in Figure 1a. Recycled aggregate sample is shown in Figure 1b. The properties of aggregates obtained experimentally as per IS: 383-1970 (52) is given in Table 2.

Table 2: *Properties of fine and coarse aggregates*

Characteristics	Value obtained by experiment as per IS: 383-1970		
	Fine aggregate	Natural Coarse aggregate (NCA)	Recycled Coarse aggregate (RCA)
Specific gravity	2.69	3.06	2.68
Fineness modulus	3.214 (Zone 1)	7.96	6.91
Water absorption (%)	0.14	0.34	1.36
Bulk density (kg/m^3)	1598	1424	1577
Abrasion value (%)	-	27.02	26.91
Impact value (%)	-	26.46	25.01
Crushing value (%)	-	31.60	30.70

Figure 1a: *Source of recycled aggregate*

Figure 1b: *Recycled aggregate sample*

2.2 Details of concrete mix

A concrete mixture of M30 was designed without recycled aggregate as per standard specification IS 10262-1982 (48) to achieve target mean strength 39 Mpa. Mix design proportion was (1: 1.15: 2.73) and w/c is 0.40. The other five concrete mixtures were made by replacing NCA with 10%, 20%, 30%, 40%

and 50% of RCA by mass and with two types of cement i.e OPC and PPC. Concrete mix proportion along with their identification was designated according to their replacement ratio as given in Table 3.

Table 3: *Concrete mix identification and Proportion*

Mix Identification	Concrete mix Proportion
CARR0	M30 Concrete without replacement of RCA (100% NCA)
CARR0.1	M30 Concrete with 10% replacement of RCA
CARR0.2	M30 Concrete with 20% replacement of RCA
CARR0.3	M30 Concrete with 30% replacement of RCA
CARR0.4	M30 Concrete with 40% replacement of RCA
CARR0.5	M30 Concrete with 50% replacement of RCA

2.3 Details of experiment

The fresh concrete test was conducted to know the workability of concrete. Slump test and compaction factor test was conducted. The slump values were remaining between 30 - 50 mm. Compaction factor values were remaining between 0.80 - 0.85. As replacement of RCA increases, the slump value decreases. The hardened concrete specimens were tested after 7, 28, and 90 days of curing. The test specimens were cast in steel mould with proper compaction and demoulded after 24 hours. The specimens such as cubes (150 x 150 x 150) mm and cylinders (100 mm diameter x 200 mm height) for compressive strength, prism (100 x 100 x 500) mm for flexural strength and cylinder (100 mm diameter x 200 mm height) for split tensile strength were cured till the day of testing under water at normal temperature and humidity conditions. The compressive strength, flexural strength and split tensile strength of the concrete specimens were tested after 7, 28 and 90 days.

2.3.1 Compressive Strength

Compressive strength is the capacity of a material or structure to withstand axially directed pushing forces. When the limit of compressive strength is reached, materials are crushed. The test on cubes and cylinder were carried out using the compressive testing machine. The compressive strength was computed by using the expression $F_c = P/B^2$ for cubes and $F_c = 4P/\pi D^2$ for Cylinders. The test setup for compressive strength of cubes and cylinders are shown in Figures 2-3. Where, F_c = Compressive strength in Mpa, P = Maximum applied load in kN, B = Size of the cubes specimen in mm, D=Diameter of the Cylinder specimen in mm.

Figure 2: *Compressive strength of cubes*

Figure 3: *Compressive strength of cylinders*

2.3.2 Split Tensile Strength

A method of determining the tensile strength of concrete using a cylinder which splits across the vertical diameter is called the split tensile strength test. The split tensile strength was computed by the expression, $F = 2P/\pi LD$. Where, F = Split tensile strength in Mpa, P = Maximum compressive load on the cylinder, L = Length of the cylinder in mm, D = Diameter of the cylinder in mm. The test setup for split tensile strength of cylinders is shown in Figure 4.

Figure 4: *Split tensile strength of cylinders*

2.3.3 Flexural strength

Flexural strength is the strength of beam or slab in bending. All the specimens were failed within the middle third of the prism. So, Flexural strength was computed using the expression, $F_b = PL/BD^2$, where, F_b = flexural strength in Mpa, P = maximum applied load kN, L = Span length, B = width of the specimen in mm, D = depth of the specimen in mm. The flexural strength test setup is shown in Figure 5.

Figure 5: *Flexural strength of prisms*

3. Experimental results and discussions

The hardened concrete properties such as compressive strength, flexural strength and split tensile strength were measured for two types of cement (OPC and PPC) with various replacement ratio of recycled coarse aggregate and results are presented in Tables 4-7, along with their graphical plots and discussions.

3.1 Compressive Strength

Nine concrete cubes and nine concrete cylinders were cast for each concrete mix proportions prepared with OPC, PPC and different coarse aggregate replacement ratios (CARR). The compressive strength of three cubes and three cylinders were measured after 7, 28 and 90 days of curing under water. The test results of cubes and cylinders are presented in Tables 4-5. The results showed that at the same curing age, all RAC had compressive strength lower than that of normal concretes for concrete mix prepared by both types of cement i.e. OPC and PPC. This is because the recycled aggregate had attached mortar, which had a higher porosity and was weaker than crushed limestone.

Table 4: *Compressive strength result of cubes*

Concrete Mix	Compressive Strength of Cubes in Mpa					
	7 Days		28 Days		90 Days	
	OPC	PPC	OPC	PPC	OPC	PPC
CARR0	33.86	32.58	42.25	41.95	45.98	46.50
CARR0.1	32.78	31.76	40.75	40.26	45.10	45.28
CARR0.2	32.25	31.50	39.56	39.50	44.30	44.70
CARR0.3	31.86	30.10	39.12	38.81	42.15	42.35
CARR0.4	30.75	29.06	36.85	36.05	39.45	40.28
CARR0.5	29.23	28.90	35.50	35.75	38.95	39.80

Table 5: *Compressive strength result of cylinders*

Concrete Mix	Compressive Strength of Cylinders in Mpa					
	7 Days		28 Days		90 Days	
	OPC	PPC	OPC	PPC	OPC	PPC
CARR0	24.28	23.13	37.35	36.67	39.48	40.10
CARR0.1	23.26	22.14	35.75	35.25	38.85	39.50
CARR0.2	22.24	20.92	34.38	34.10	38.35	38.95
CARR0.3	21.45	19.56	32.10	31.39	36.95	37.80
CARR0.4	20.35	18.90	30.35	29.96	35.45	36.25
CARR0.5	19.45	18.36	28.36	28.16	33.65	34.86

Figures 6-7 show the graphical representation of compressive strength and age in days for the concrete cubes and cylindrical specimens. Figures 8-9, represent the relation between compressive strength of concrete cubes and cylinders and CARR for 7, 28 and 90 days. From Figures 6-7, it is observed that the compressive strength of concrete increases as curing age increases for both mix proportions of concrete made by two different types of cement. It is also observed that concrete prepared by PPC shows comparatively lower compressive strength than OPC at early age (7 days), whereas at 28 days it shows almost equal value, but in later age i.e after 90 days PPC shows comparatively higher value than OPC. From Figures 8-9, it is observed that as CARR increases the compressive strength of concrete decreases for both types of cement OPC and PPC. Upto 20% recycled aggregate replacement (RAR), there is no remarkable change in compressive strength as compared with the concrete prepared by NCA. It is also observed that the compressive strength of concrete attains more than the target mean strength upto 20% replacement of RA. Thereafter as CARR increases, the compressive strength of concrete is less than the target mean strength.

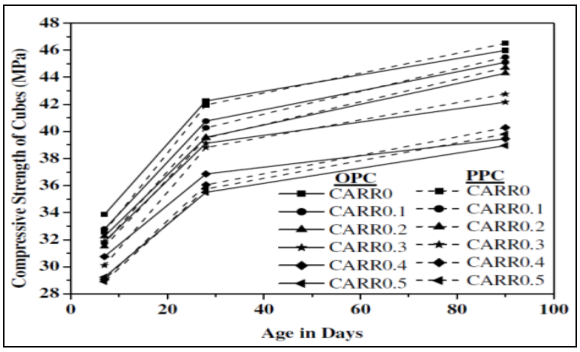

Figure 6: *Compressive strength of cubes with age*

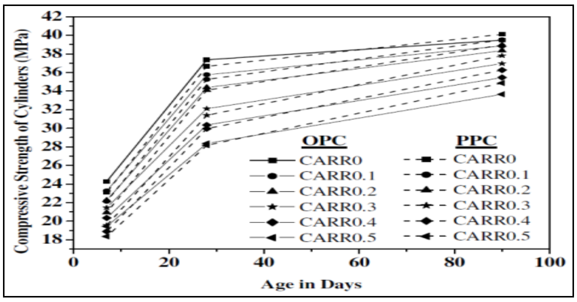

Figure 7: *Compressive strength of cylinders with age*

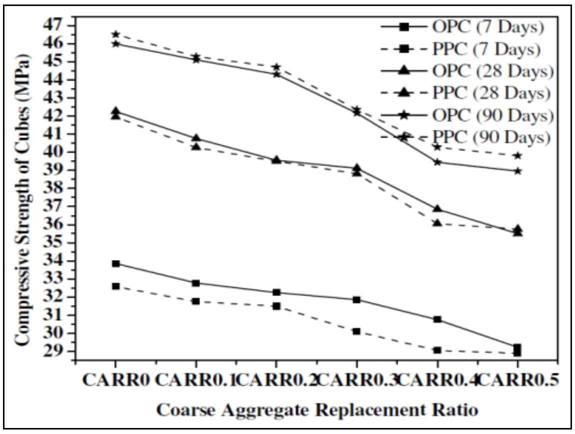

Figure 8: *Compressive strength of cubes with CARR*

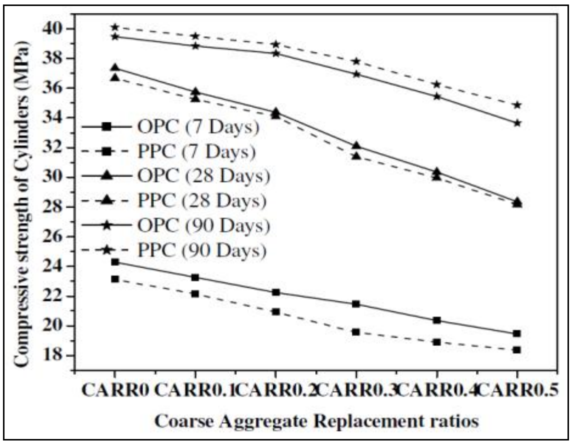

Figure 9: *Compressive strength of cylinders with CARR*

3.2 Flexural Strength

The flexural strength of concrete prism of size (100 mm × 100 mm × 500 mm) is measured after 7 and 28 days of curing under water. Table 6 presents the experimental and theoretical flexural strength results of concrete prism for both types of cement i.e. OPC and PPC. The theoretical flexural strength is calculated using the equation ($f_{cr}= 0.7\sqrt{f_{ck}}$) for both types of cement. Where, f_{cr} is the theoretical flexural strength of concrete prism and f_{ck} is the characteristics strength of concrete after 28 days.

Table 6: *Flexural strength result of prisms*

Concrete Mix	Experimental flexural strength of prism in Mpa				Theoretical flexural strength at 28 days in Mpa. ($f_{cr}= 0.7\sqrt{f_{ck}}$)	
	OPC (7 Days)	PPC	OPC (28 Days)	PPC	OPC	PPC
CARR0	3.95	3.90	5.12	5.07	4.55	4.53
CARR0.1	3.90	3.88	5.07	5.01	4.46	4.44
CARR0.2	3.82	3.77	4.92	4.85	4.40	4.40
CARR0.3	3.53	3.46	4.35	4.55	4.37	4.36
CARR0.4	3.40	3.32	4.08	4.25	4.25	4.20
CARR0.5	2.92	2.91	3.65	3.92	4.17	4.18

Figure 10 shows the graphical plot between flexural strength of concrete and age in days. Figure 11 shows the graphical plot between flexural strength of concrete and CARR at 7 days and 28 days. The theoretical flexural strength is also compared for both types of cement and as shown in Figure 11. It is observed from the Figures 10-11, the flexural strength of concrete prepared by OPC and NCA is higher than PPC and NCA after 7 and 28 days. As CARR increases, the flexural strength of concrete decreases in specimen prepared with both OPC and PPC. The flexural strength of concrete specimen is not much affected upto 20% replacement of coarse aggregate and is close to the value of conventional concrete. It is also observed that the theoretical flexural strength of concrete is less than the experimental flexural strength of concrete specimen prepared by OPC and upto approximately 30% replacement of coarse aggregate and by PPC and upto approximately 40% replacement of coarse aggregate, thereafter the experimental value is less than the theoretical value.

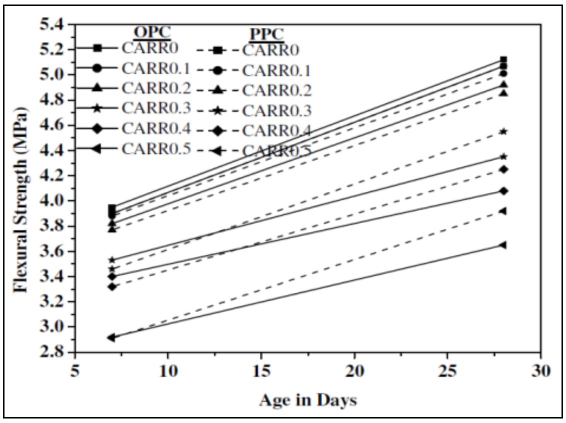

Figure 10: *Flexural strength of concrete with age*

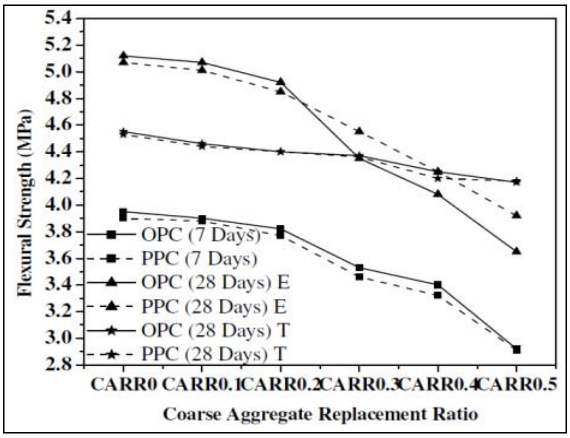

Figure 11: *Flexural strength of concrete with CARR*

3.3 Split Tensile Strength

The split tensile strength is conducted on cylindrical specimen of size (200 mm × 100 mm). The split tensile strength of concrete is measured after the curing period of 7, 28 and 90 days. The test results are presented in Table 7.

Figure 12 shows the graphical plot between split tensile strength and age in days of the concrete cylinder. Figure 13 shows the split tensile strength of concrete against the variation of CARR at 7, 28 and 90 days. It is observed from the plot that, the split tensile strength of concrete increases, as curing period increases for all mix proportions. The rate of increment of split tensile strength is more upto 28 days. As cement concern, the early age split tensile strength (7 days) is higher in concrete specimen prepared with OPC and later age strength (90 days) is higher in concrete specimen prepared with PPC. The split tensile strength is continuously decreases as CARR increases for mixes prepared by both OPC and PPC.

Table 7: *Split tensile strength result of cylinders*

Concrete Mix	Split tensile Strength of Cylinders in Mpa					
	7 Days		28 Days		90 Days	
	OPC	PPC	OPC	PPC	OPC	PPC
CARR0	3.25	3.03	4.64	4.62	5.32	5.41
CARR0.1	2.95	2.90	4.41	4.39	5.12	5.22
CARR0.2	2.90	2.80	4.22	4.20	4.98	5.13
CARR0.3	2.78	2.67	3.85	3.98	4.78	4.90
CARR0.4	2.62	2.51	3.76	3.79	4.50	4.75
CARR0.5	2.52	2.29	3.42	3.50	4.20	4.59

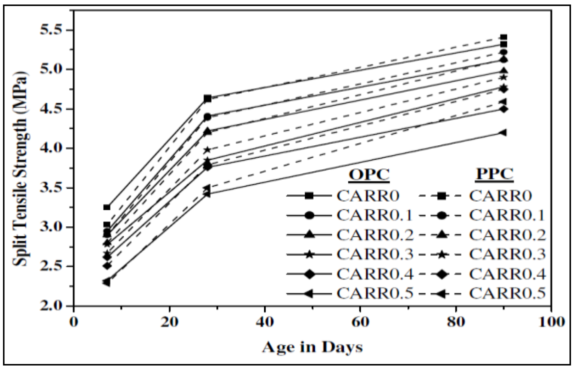

Figure 12: *Split tensile strength of concrete with age*

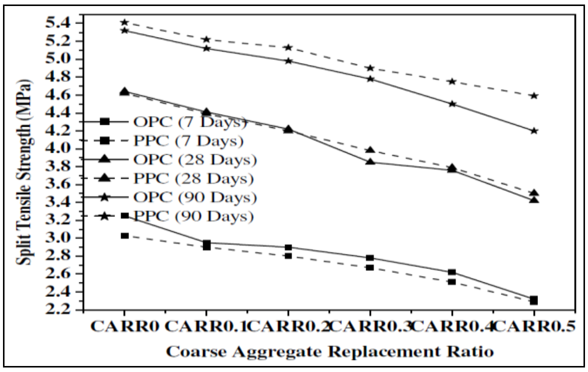

Figure 13: *Split tensile strength of concrete with CARR*

4. Concluding remarks

The result of compressive strength, flexural strength and split tensile strength of concrete specimens prepared with OPC and PPC and with various coarse aggregate replacements is presented. Based on the above results the following conclusions may be drawn:

- The workability of concrete decreases as CARR increases for both types of cement.
- The test results indicate that the compressive strength, flexural strength and split tensile strength of concrete is higher in concrete made with NCA than concrete made with RCA.
- As cement concern, the early age compressive strength of concrete made with OPC is higher than PPC, whereas in later age PPC is higher than OPC.
- The compressive strength, flexural strength and split tensile strength of concrete gradually decreases with increase in CARR in both OPC and PPC.
- The compressive and flexural strength of concrete prepared with RCA is not much affected up to 20% of recycled aggregate and is close to the value of conventional concrete.
- The theoretical flexural strength is less than the experimental flexural strength of concrete upto approximately 30% and 40% of CARR and prepared by OPC and PPC respectively, thereafter the experimental value is less than the theoretical value.

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