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PERFORMANCE OF HIGH STRENGTH RECYCLED AGGREGATE CONCRETE USING METAKAOLIN

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Abstract— This present study aims to investigate experimentally the use of recycled aggregates in high strength concrete using metakaolin as a mineral admixture. In this study, the natural fine aggregates were replaced with recycled fine aggregates (RFA) at 10%, 20%, 30%, 40% and 50% while keeping a constant replacement of recycled coarse aggregate (RCA) at 30%. The compressive as well as durability properties like acid resistance and sulphate attack have also been investigated. It was observed that the replacement of sand with RFA up to 10% gave higher strength than the normal control mix (NCM) in terms of compressive strength at later ages. The specimens exposed to sulphate attack also showed a similar trend in terms of compressive strength.

Keywords— recycled aggregate (RA), recycled fine aggregate (RFA), high strength concrete (HSC), durability, metakaolin, sulphate attack, acid resistance, compressive strength

1. Introduction

The growth rate of urbanization in India is very high due to the rapid industrialization. Hundreds of concrete structures are being constructed on a daily basis. This increases the demand of the raw materials needed for construction i.e. cement, aggregates, sand etc. The increase in the demand leads to deterioration of the natural resources and environmental degradation, also this rapid industrialization results in demolition of old concrete structures to build new ones. Using crushed concrete as fill and sub-grade material for roads, sidewalks and foundations is a common practice. However, research has been going on worldwide over the years to investigate the use of crushed concrete from demolished old concrete structures to fully or completely replace the natural aggregates in concrete structures. The use of recycled aggregates in concrete is relatively an unexplored research area and the experimental data is limited on it. A study considering high strength concrete containing 30% RCA replacement and varying replacement percentages of RFA (10%, 20%, 30%, 40%, 50%) were considered. 30% replacement value of RCA was chosen as a similar RCA replacement percentage did not have any effect on compressive strength of high strength recycled aggregate concrete, a similar pattern was reported by other researchers [7]. This paper examines the influence of RCA and RFA on high strength concrete. Its performance by acid resistance and sulphate attack test were examined along with the compressive strength.

2. EXPERIMENTAL STUDY

2.1 Materials used

In the present study, crushed concrete specimens from the college laboratory were used to produce RCA and RFA in this study because of their availability in large quantity and furthermore, they are clean and free from any chemical impurities. A jaw crusher was used to produce RCA and RFA of required size. Natural coarse aggregates of 10 and 20 mm size and natural sand of zone II conforming to IS 383:1970 were procured locally. The physical properties of RCA were determined in accordance with IS 2386:1963 and RFA are tabulated in Table 1.

Table 1 Physical properties of RFA and RCA

S.no	Type	Specific Gravity	Water absorption
1	RCA (20mm)	2.38	2.84 %
2	RCA(10mm)	2.45	3.11 %
3	RFA	2.51	9.29 %

Ordinary Portland cement (OPC) of 43-grade was used in this study. The normal consistency of cement used was found to be 29.5%. High reactive metakaolin was procured from KaoMin Industries in Vadodara, Gujarat and the replacement percentage of metakaolin was kept at 15 % only as the RAC mixes had shown best performance at this replacement level by previous researchers [9]. The specific gravity and bulk density of metakaolin was reported as 2.6 and 360 Kg/m3 respectively by the supplier. BASF Master Glenium Sky 8866 was used as a super plasticizer. It is a high-performance super plasticizer based on PCE (polycarboxylic ether) for concrete with a specific gravity of 1.08 at 25°C.

2.2 Mix proportioning

Concrete mix has been designed using the ACI 211.4R08. All the mixes are designed by keeping the water content constant. To achieve the required workability of concrete mix, super plasticizer is added to the concrete mix at a desired dosage rate. The mix design details are shown in Table 2.

Table 2 Concrete mix design details

Grade of concrete	M60
Water / binder ratio	0.27
OPC	435 Kg/m^3
Metakaolin (15 % of cement)	76 Kg/m^3
Coarse aggregate	1108 Kg/m^3
Fine aggregate	625 Kg/m^3
Water	138 Kg/m^3
Super plasticizer	5.1 Kg/m^3
Target slump	80 – 100 mm

3. RESULTS AND DISCUSSION

3.1 Compressive strength

The tests were conducted at curing ages of 28, 56 and 90 days respectively conforming to IS: 516– 1959.

Table 3 Compressive strength of mixes at 28, 56 and 90 days

Mix designation	28 day compressive strength **(N/mm^2)**	56 day compressive strength **(N/mm^2)**	90 day compressive strength **(N/mm^2)**	% increase at 56 day w.r.t 28 day **(N/mm^2)**	% increase at 90 day w.r.t 28 day **(N/mm^2)**
NCM	62.12	62.65	62.94	0.84	1.30
RFA 10	57.20	62.84	63.52	8.97	9.94
RFA 20	59.15	60.20	61.55	1.74	3.89
RFA 30	48.47	53.52	56.32	9.43	13.93
RFA 40	41.95	53.32	55.32	21.32	24.16
RFA 50	40.70	52.48	52.61	22.44	22.69

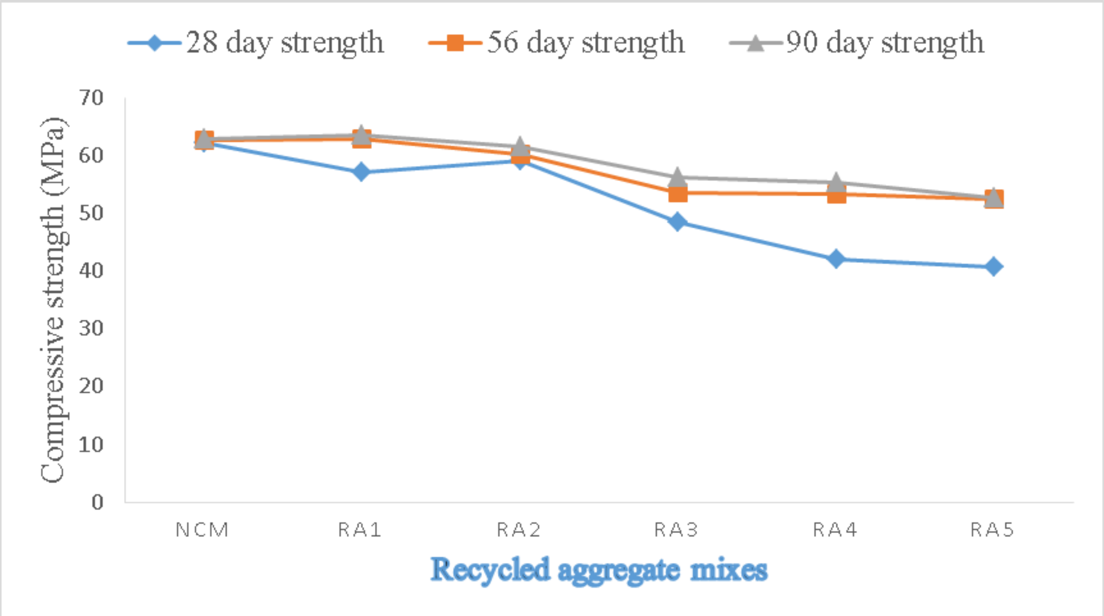

Fig 1 Comparison of compressive strength at different curing ages

It is clear from Fig 1 and Table 3 that RFA10 mix showed best results in terms of compressive strength at later ages i.e. at 56 & 90 days. It is also observed that RFA20 mix exhibited a higher compressive strength at 28 days as compared to other mixes except NCM. This might be due to the continuous hydration of unhydrated cement in RFA as this provides additional bonding strength in the ITZ, a similar trend was also reported by Braga et al (2012) [6]. It can also be seen that the compressive strength of the RFA30, RFA40 and RFA50 mixes improve significantly compared to other mixes with increase in curing age. This increase is a result of the increased pozzolonic activity of metakaolin in concrete during the later ages. This can be explained by the chemical and pozzolonic property of metakaolin, which result in its high reactivity. As the replacement percentages were increased, the compressive strength decreased and it was the lowest for RFA50 mix at 28, 56 and 90 days respectively.

3.2 Acid resistance

For each mix, three cubes were cast for acid resistance test and placed in a 2.5 % acid solution for 56 days after curing them for 28 days in water. The pH of the solution was maintained for the entire period. After 56 days, the specimens were removed from the acid solution and cleaned and dried for 24 hours. The specimens were then weighed using an electronic scale to determine percentage loss in mass and tested for loss in compressive strength.

Fig 2 Specimen after being immersed in acidic solution for 56 days

Table 4 Mass loss in specimens being exposed to acidic solution

Mix designation	Initial weight (Kg)	Final weight (Kg)	Loss (%)	Average loss (%)
NCM	8.20	7.94	3.17	3.02
	8.11	7.89	2.71	
	8.16	7.90	3.18	
RFA10	8.18	7.87	3.78	4.22
	8.20	7.85	4.26	
	8.19	7.81	4.63	
RFA20	8.17	7.80	4.52	4.29
	8.05	7.71	4.22	
	8.2	7.86	4.14	
RFA30	8.15	7.70	5.52	4.78
	7.96	7.65	3.89	
	8.09	7.69	4.94	
RFA40	7.94	7.56	4.78	5.02
	8.02	7.58	5.48	
	7.89	7.51	4.81	
RFA50	7.82	7.41	5.24	5.19
	7.78	7.38	5.14	
	7.88	7.47	5.20	

It is clear from the Table 4 that the highest mass loss was seen in RFA50 at 5.19% and the least was observed in the control mix at 3.02%. A lower mass loss indicates higher acid resistance, it can be seen that on increasing the RFA content, the loss in mass also increased after being exposed to acidic solution. Further, the loss in compressive strength was also observed for the specimens immersed in acid solution. The results of the compressive strength are tabulated in Table 5 along with the loss in compressive strength as compared to their respective 90 day compressive strength.

Table 5 Compressive strength of specimens immersed in acid solution

Mix designation	Peak load at failure (kN)	Compressive strength (N/mm^2)	Average compressive strength (N/mm^2)	Loss in compressive strength (%)
NCM	1305	58	57.48	8.67
	1281	56.93		
	1294	57.51		

RFA10	1275	56.66	56.63	10.84
	1257	55.86		
	1291	57.37		
RFA20	1181	52.48	53.04	13.82
	1209	53.73		
	1191	52.93		
RFA30	1009	44.84	45.38	19.42
	1059	47.06		
	996	44.26		
RFA40	982	44.23	42.46	23.24
	972	43.20		
	899	39.95		
RFA50	911	40.48	39.17	25.54
	893	39.68		
	841	37.37		

It is clear from the Table 5 that with increase in the percentage of RFA, the compressive strength was drastically affected when exposed to acidic solution. The factor determining the acid attack is the permeability in concrete, which depends on the porosity, size of the pores, continuity of the pores and its distribution. Concrete containing recycled aggregate exhibits a poorer paste structure and has a greater porosity compared to the control concrete mix. This results in a less dense hydrated cement paste with more pores leading to quicker leaching out of calcium from C-S-H and $Ca(OH)_2$. As a result, the acid resistance of RA concrete decreases with increase in RA content.

3.3 Sulphate attack

For each mix, three cubes were cast for sulphate attack test and placed in a 5 % magnesium sulphate solution for 56 days after curing them for 28 days in water. The specimens were then weighed using an electronic scale for mass change and then for change in compressive strength. The results of change in mass are tabulated in Table 6.

Table 6 Mass loss in specimens being exposed to sulphate solution

Mix designation	Initial weight (Kg)	Final weight (Kg)	Loss (%)	Average loss (%)
NCM	8.25	8.26	-0.12	-0.08
	8.17	8.17	0.0	
	8.23	8.24	-0.12	
RFA10	8.26	8.28	-0.24	-0.2
	8.20	8.21	-0.12	
	8.19	8.21	-0.24	
RFA20	8.10	8.13	-0.37	-0.28
	8.05	8.08	-0.37	
	8.13	8.14	-0.12	
RFA30	8.01	8.02	-0.12	-0.16
	7.93	7.95	-0.25	
	7.98	7.99	-0.12	
RFA40	7.92	7.92	0	-0.04
	8.00	8.01	-0.12	
	7.95	7.95	0	
RFA50	7.76	7.77	-0.13	-0.08
	7.78	7.78	0	
	7.88	7.89	-0.12	

The negative value of mass loss indicates a mass gain in the specimens. All the specimens showed a gain in mass at the end of 56 days. The interaction of Ca^{2+} ions with SO_4 present in the solution will produce gypsum which further reacts with C_3A and produces ettringite. The formation of these new products results in an overall mass gain as these new crystals occupy the empty space in concrete. It is hypothesized that the rise in mass is due to reaction of the sulphate with the surface layers which are rich in cement paste. Once this initial layer of cement has reacted, the sulphates must diffuse into the bulk concrete to react with the cement then the rate of reaction is slowed and the rate of increase in mass is also reduced. The specimens were tested for change in compressive strength and the results as compared to the results of 90 day cured specimens are tabulated in Table 7.

Table 7 Compressive strength of specimens immersed in sulphate solution

Mix designation	Peak load at failure (kN)	Compressive strength (N/mm^2)	Average compressive strength (N/mm^2)	Loss in compressive strength (%)
NCM	1423	63.24	62.99	-0.08
	1411	62.71		
	1418	63.02		
RFA10	1439	63.95	64.04	-0.81
	1428	63.46		
	1456	64.71		
RFA20	1404	62.40	61.99	-0.71
	1392	61.86		
	1389	61.73		
RFA30	1271	56.48	56.41	-0.15
	1251	55.60		
	1259	55.95		
RFA40	1135	50.44	51.55	6.78
	1195	53.11		
	1150	51.11		
RFA50	1005	44.66	44.61	15.19
	997	44.31		
	1010	44.88		

As it is clear from the table that there is gain in strength in mixes RFA10, RFA20, and RFA30 whereas loss in compressive strength can be seen in case of RFA40, RFA50 and the control mix. A higher replacement of recycled aggregate leads to increase in ITZ in the concrete which makes it feasible to sulphate attack. A higher replacement of natural sand with RFA resulted in poor resistance against sulphate attack. Whereas, the increase in strength of RFA10, RFA20 and RFA30 can be attributed to the inclusion of metakaolin in the mix. Metakaolin reacts with $Ca(OH)_2$ present in the concrete to produce C-S-H gel which means there is reduction in Ca^{2+} ions in the concrete paste to react with sulphate ions that further produce gypsum and ettringite.

4. CONCLUSIONS

On the basis of results and discussions, the following conclusions are drawn:

- Although the 28 day compressive strength was lower for all the mixes having recycled aggregate than the control mix, the 56 and 90 day compressive strength were more for RFA10 concrete mix. This increase in strength may be attributed to the increased pozzolonic activity of the metakaolin in concrete. Even though, the compressive strength of the RFA20 mix is lower than the control mix, the variation in strength is minimal. We can conclude that high strength concrete can still be produced at 20% replacement of natural sand with RFA and 30% replacement of natural coarse aggregate with RCA.
- The acid resistance test shows a gradual increase in the loss in weight with increasing RFA replacement. The control mix showed best results in terms of loss in weight as compared to the recycled aggregate concrete. A similar trend of loss in compressive strength was also observed, this may be attributed to the increased replacement of natural aggregate by recycled aggregates in the concrete mix as this leads to formation of more ITZ layers in the concrete and these ITZ layers are susceptible to the acid attack.
- The sulphate attack shows a gain in weight as opposed to loss in weight in the acid resistance test in all the mixes. This is mainly due to the formation of new products such as gypsum and ettringite in the early period. Also, a gain in compressive strength was observed in all specimens except RFA40 and RFA50. The increase in the replacement of natural aggregates by recycled aggregates might be the reason for this. As the permeability of the concrete increases due to high porosity of recycled aggregates and the sulphate ions can attack the paste easily.
- The compressive strength of RFA10 and RFA20 showed a gain of 0.81% and 0.71% respectively as compared to a gain of only 0.08% in the control mix. This might be attributed to the inclusion of metakaolin in the recycled aggregate concrete that reacts with Ca(OH)2 to produce more C-S-H gel. Clearly RFA10 and RFA20 showed better results than the control mix and based on these results, we can recommend RFA10 and RFA20 to be used in high strength concrete.

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