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MECHANICAL AND DURABILITY PROPERTIES OF SLAG BASED RECYCLED AGGREGATE CONCRETE*

P. SARAVANAKUMAR AND G. DHINAKARAN**
School of Civil Engineering, SASTRA University, Thanjavur 613401, India
Email: gd@civil.sastra.edu

Abstract– In this paper, the possibility of using recycled aggregate (RA) and ground granulated blast furnace slag (GGBFS) to produce a structural concrete was studied by compromising strength to a lesser extent. Hence an attempt has been made to study the strength and durability characteristics of the GGBFS-based recycled aggregate concrete. Four different groups of mixes were designed by replacing natural coarse aggregate (NA) 0, 25, 50 and 100% with recycled coarse aggregates. In each group the effect of RA was studied by replacing cement with GGBFS in different percentages from 20 to 50% with an increment of 10%. The effects of RA and GGBFS on fresh and hardened concrete properties were studied and the results were compared with natural aggregate concrete (NAC) and optimum replacement of RA and GGBFS was also found. Experimental results indicate that increase in concrete strength for all NA replacements with RA for GGBFS concrete upto 40% at the age of 90 days and further addition of GGBFS shows reverse trend.

Keywords– Natural aggregate, recycled aggregate, ground granulated blast furnace slag, recycled aggregate concrete, compressive strength, chloride ion penetration

1. INTRODUCTION

Depletion of natural aggregates, rapid increase in construction and demolition wastes and mass production of cement are the critical issues that create a threat to environment and more concern for the construction industry. The recycle and reuse of such construction and demolition waste materials will yield a tangible impact for protecting the environment specifically and controlling the cost of the construction in general. For the past two decades, a number of scientists and researchers focused on the possible of use of recycled aggregate in producing new concrete and found that the results were encouraging. It was assessed that release of carbon dioxide due to production of cement contributes to 7% of the total green house gas emissions [1, 2]. The use of recycled aggregate, preferable to mineral admixtures also became the preferred choice due to the above-mentioned problem, in addition to solving the disposal problem of dumped waste from thermal and steel industries and enhancing the strength and durability criteria. A number of such mineral admixtures like fly ash (FA), micro silica, meta-kaolin and GGBFS were tried in the field. The use of partial replacement of cement with GGBFS in concrete has been accepted in countries like South Africa, Australia, the UK, Japan, Canada, and the USA since the late 1950s [3]. The concrete having slag-cement combination has lowered early age strength particularly at low temperatures or with high slag percentages [4]. Many researchers have studied the effect of slag on concrete properties and reported encouraging results for the replacement of cement with slag in concrete.

The effect of percentage replacement of cement with GGBFS on concrete compressive strength was studied and reported 55% replacement level of GGBFS attained the maximum strength improvement and

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**Corresponding author

further addition GGBFS did not improve the compressive strength [5]. Curing condition and GGBFS replacement level had significant effects on the strength and durability characteristics [6]. The strength of the concrete at the early age reduces when the slag replacement is more than 50%. However, at a later age, the strength improvement was noticed in the concrete with the presence of slag up to 60% replacement.

To meet the environmental challenges the utilization of supplementary cementitious material such as GGBFS, fly ash, etc. and recycled aggregates in concrete industry is very important [7]. Recycled aggregate concrete showed slight increase in coefficient of permeability and chloride diffusion coefficient than control concrete. But the overall performance of recycled aggregate concrete with 50% slag was good. However, the values remained acceptable for durable concrete. The slag incorporation in concrete improves the chloride diffusion characteristics of the concrete [8].

From earlier research it was found that though the addition of mineral admixtures makes some improvement in the strength and durability of concrete with natural aggregate and recycled aggregate, it gives better results on recycled aggregate concrete than natural aggregate concrete. SF and MK gives better results both in short term and long term properties whereas FA and GGBFS gives better results only at the later age. Replacement of cement with 55% of GGBS decreased the compressive strength, but improved the durability properties of the recycled aggregate concretes [9]. The replacement of cement with FA and GGBFS affects the compressive strength at all ages up to 91 days. It was possible to enhance the long-term compressive strength of both FA and GGBFS mixes with the addition of 7.5% of SF [10].

Authors of the present paper have done extensive experimental investigations on strength and durability characteristics of recycled aggregate concrete with high volume fly ash. The authors found that the age and source of the recycled aggregate concrete of RA influence the compressive strength. They also investigated the effects of replacing natural aggregate with recycled aggregate from 25 to 100% and cement with fly ash from 40 to 60% in concrete and studied the compressive and tensile strength of concrete with characteristic compressive strength of 50 MPa. The authors concluded that the experimental results with 50% replacement of cement with fly ash and 50% replacement of NA with RA gives satisfactory results by compromising strength to an extent of 40 to 50% with major reduction in cost [11-15].

The present paper reports the experimental results of a systematic study on the effect of recycled aggregate and GGBFS on strength characteristics such as compressive strength and tensile strength and durability characteristics such as resistance against capillary suction and chloride ion penetration of GGBFS based recycled aggregate concrete.

2. RESEARCH SIGNIFICANCE

Different materials as a substitute to cement were developed and tried in the field of concrete construction to minimize the usage of cement thereby reducing environmental problems. Most of the studies have concentrated on strength and durability characteristics of concrete by replacing either cement or other ingredient separately. Only limited studies were available on studies with combined replacement of cement and coarse aggregate that too on durability criteria. In the present work authors have done detailed experimental investigations on strength and durability characteristics of slag based recycled aggregate concrete, which will be the need of the hour in the area of concrete technology.

3. EXPERIMENTAL INVESTIGATIONS

a) Materials

ASTM type 1 Portland cement and GGBFS were used as cementitious materials in the concrete mixtures. Locally available river sand as fine aggregate and crushed granite stones and recycled aggregates retrieved from 20 year old demolished structures of maximum 16 mm size as coarse aggregate was used in the concrete matrix. Specific gravity and fineness modulus of sand used was 2.72 and 1.97 respectively and fall under grade zone III. Similarly the specific gravity of natural and recycled coarse aggregate used was 2.7 and 2.60 respectively.

b) Characterization of recycled aggregate

The recycled aggregates were cleaned and washed before using for concreting to remove the dust and adhered particles from the aggregate. First the demolished concrete was subjected to crushing and unwanted materials like steel, soil and other contaminated material were removed. After that, it was further crushed to obtain the desired size. Finally the crushed aggregates were subjected to washing and dry/wet screening to remove fine impurities, such as a soil and adhered loose cement mortar in the aggregate. The chemical composition of the materials used in the present study was found through XRF analyzer. The values are given in Table 1 and it was confirmed that the GGBFS satisfied the requirements of ACI 233R-03 [3]. Physical and mechanical properties of coarse aggregates used are given in Table 2.

According to RILEM Technical Committee 121-DRG (RILEM 1994), RA are classified into three groups: Group I: aggregates produced mainly from masonry rubble, Group II: aggregates obtained from concrete rubble, Group III: a mixture of NAs (> 80%) and rubble from the other two groups (with up to 10% of Group I, and Group II aggregate). These can be used for the production of all types of concrete. From Tables 1 and 2, the RA standard was verified with RILEM Technical Committee 121-DRG (RILEM 1994) report [16] and it was confirmed that Group II RA was used for this entire work. The NA and RA used for the work were shown in Figs. 1 and 2.

Table 1. Chemical composition of materials used

Description	SiO_2	Al_2O_3	CaO	Fe_2O_3	Na_2O	MgO	K_2O
Natural Aggregate (%)	58.54	17.81	6.17	6.07	4.20	2.91	2.65
Recycled Aggregate (%)	56.89	10.57	19.93	3.85	1.92	0.60	4.15
Cement (%)	24.50	7.00	63.00	0.55	0.40	2.00	0.60
GGBFS (%)	34.01	16.62	34.85	1.71	0.48	9.11	0.46

Table 2. Physical and mechanical properties of Coarse aggregates

Description	Natural Aggregate	Recycled Aggregate
Specific gravity	2.70	2.60
Water absorption (%)	3.00	4.50
Aggregate crushing value (%)	17.70	31.20
Aggregate impact value (%)	5.80	18.50
Fineness modules	7.02	6.93

Fig. 1. Natural aggregates

Fig. 2. Recycled aggregates

A total of four series of mixtures were prepared with RA replacements of 0%, 25%, 50% and 100% named as series I, II, III and IV respectively. In each series, cement was also replaced with GGBFS by 20%, 30%, 40% and 50%. ACI 211.1-91 [17] method was used for designing the concrete mix. The grade of concrete used for the present work was M50 (with a characteristic compressive strength of 50 MPa). The mix proportion derived was 1:0.7:2.3 with the water cement ratio of 0.36. Sulphonated polymer-based superplasticizer was effectively used as a chemical admixture to adjust consistency of cement mortar containing industrial wastes [18]. The reduction in w/c ratio with the addition of super plasticizers reduces the permeability and improves the strength characteristics of concrete [19]. In this work commercially available sulphonated naphthalene formaldehyde-based super plasticizer was used to reduce the w/c ratio from 0.36 to 0.30. The mix proportion and the material quantities were tabulated in Table 3. An initial and final setting time of RAC were found to be 280 minutes and 330 minutes respectively and was 10 minutes more than NAC. The above test was conducted as per ASTM C403-1999 [20].

Table 3. Mix proportion per m^3 of concrete

Mix Idn.	RA as a replacement (%)	GGBFS as a replacement (%)	Cement (kg)	Coarse Aggregate (kg)	Fine Aggregate (kg)	RA (kg)	GGBFS (kg)	Slump (mm)
Series 1								
M1	0	0	530	1240	389	-----	-----	88
M2	0	20	424	1240	389	-----	106	93
M3	0	30	371	1240	389	-----	159	96
M4	0	40	318	1240	389	-----	212	100
M5	0	50	265	1240	389	-----	265	104
Series 2								
M6	25	0	530	930	389	310	------	85
M7	25	20	424	930	389	310	106	89
M8	25	30	371	930	389	310	159	92
M9	25	40	318	930	389	310	212	95
M10	25	50	265	930	389	310	265	99
Series 3								
M11	50	0	530	620	389	620	-----	82
M12	50	20	424	620	389	620	106	85
M14	50	30	371	620	389	620	159	87
M15	50	40	318	620	389	620	212	91
M15	50	50	265	620	389	620	265	94
Series 4								
M16	100	0	530	-------	389	1240	-----	78
M17	100	20	424	-------	389	1240	106	82
M18	100	30	371	-------	389	1240	159	85
M19	100	40	318	-------	389	1240	212	88
M20	100	50	265	-------	389	1240	265	92

c) Specimen Details

1. Compressive and tensile strength: In each mix series 150 x 150 x 150 mm cube specimens and cylinders with 150 mm diameter and 300 mm height were cast in accordance with ASTM C-192 [21]. The cube specimens were used to determine the compressive strength and the cylinders were used to evaluate the tensile strength using split tension test. In each mix series 3 cube specimens and 3 cylinders were cast and the mix proportions for all the mixes used in the present research work was reported in Table 3. All the cast specimens were cured and tested at different ages of concrete (7, 14, 28, 56 and 90 days) to understand the effect of age of concrete. The tests to assess compressive and tensile strengths were conducted using digital compression testing machine of 3000 kN capacity with 200 kN/min and 57 kN/min as rates of loading for compressive and tensile strength tests respectively.

2. Sorptivity test: Resistance against capillary suction of concrete was measured through Sorptivity test as per ASTM C1585 [22] and was given in Fig. 3. Specimens of 100 mm diameter and 50 mm height slices were prepared by cutting the top and bottom of the 100 mm x 200 mm cylindrical concrete and preconditioned by drying the sample for 7 days in a 50°C oven and then allowed to cool in a sealed container for three days. The sides and top of the concrete sample were sealed with electrician's tape. The initial mass of the sample was noted and the sample was immersed to a depth of 5 mm in the water from the bottom ensuring that only bottom face was exposed to water. Mass of sample was noted at periodical intervals (i.e. 1 to 180 min.) by removing sample suitably. Difference in mass over a period of immersion gives an idea of the amount of water absorbed by the concrete due to capillary suction. Graph was plotted by taking gain in mass (volume of water absorbed under capillary suction) per unit area of the cylinder in the ordinate and the square root of the elapsed time in the abscissa. Figure 4 shows the effect of RA on sorption. Trend line (line of best fit) was drawn to get a slope equation and hence the sorption coefficient. Similarly the graphs were drawn for other mix combinations to find the sorption coefficient.

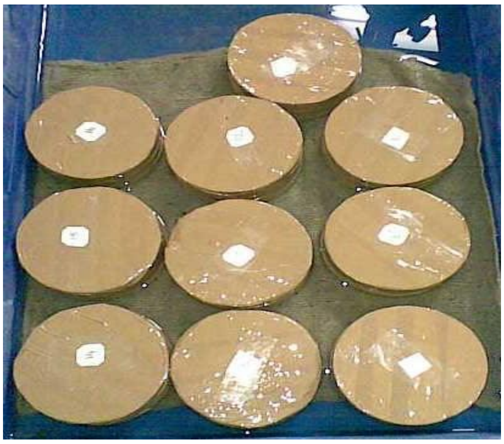

Fig. 3. RAC Specimens under Sorptivity testing

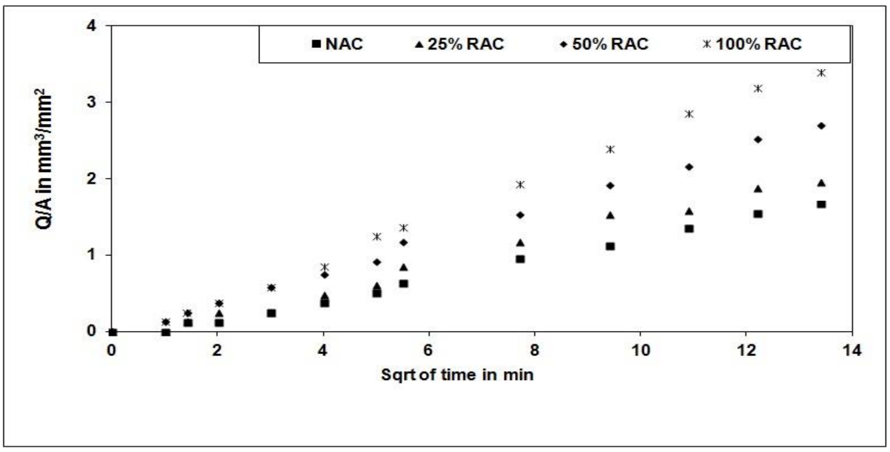

Fig. 4. Effect of RA on Sorptivity

3. Chloride ion Penetration Test: Rapid chloride ion permeability test (RCPT) was used to evaluate the permeability of GGBFS based recycled aggregate concrete. The chloride ion penetration of concrete was tested based on the standard test method of ASTM C1202 [23] using concrete specimens of 100mm diameter and 50mm height cut from 100 mm x 200 mm (diameter x height) concrete cylinder and the details of the test were given in Fig. 5. Specimens were kept in Rapid chloride penetration test apparatus and subjected to a constant DC voltage of 60V for 6 hours. The test apparatus consists of two reservoirs out of which one reservoir has 3.0 % NaCl solution and the other reservoir has 0.3M NaOH solution. The total charge passed through concrete specimen was measured and rated as per ASTM standard.

Fig. 5. RAC Specimens under RCPT testing

4. RESULTS AND DISCUSSION

a) Compressive strength

The compressive strength for different percentage replacements of NA with RA and cement with GGBFS at the age of 7, 28 and 90 days concrete is shown in Table 4. Irrespective of all replacements the result shows that the strength increases when age increases. From the 28 days experimental results it was observed that, the compressive strength of concrete reduces for all replacements (25% to 100%) of coarse aggregate (NA) with RA. For the replacement of 25% to 100% NA, the concrete mix obtained the strength of 81% to 60% of the control mix. The variation in the compressive strength improvement at the age of 28 and 90 days for mix I to IV for all cement replacements is shown in Fig. 6. From that, it is observed that for all mixes (Mix I to Mix IV) at the age of 28 days, the compressive strength reduces when the percentage replacements of cement with GGBFS increased (20% to 50%). However, the rate of strength gain increases after 28 days, irrespective of replacements of NA with RA. The compressive strength of concrete at the age of 90 days revealed that, the rate of strength gain in the concrete with more than 20% GGBFS was found to be better than that of control concrete. The rate of strength gain of concrete with 40% cement replacement has been found to be higher than the concrete with 20%, 30% and 50% cement replacement for the mix I and mix II. For mix III and mix IV, rate of strength gain of concrete with 40% cement replacement was almost equal to 50% cement replacement.

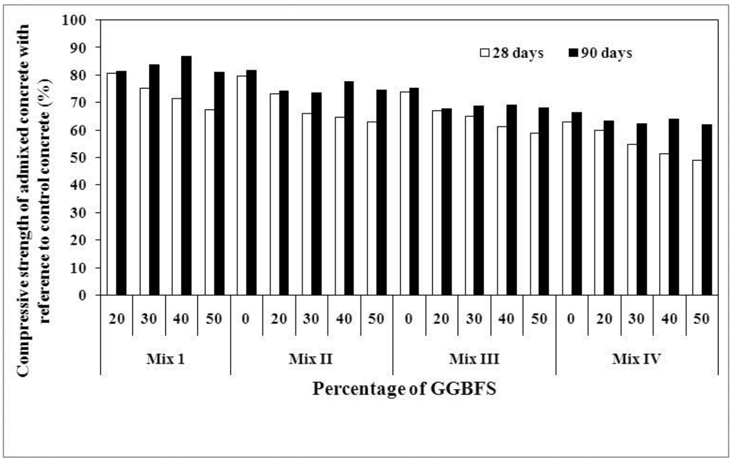

Fig. 6. Compressive strength of admixed concrete with reference to control concrete

Table 4. Compressive and Tensile strength for different mix combinations

Mix Designation	Cement replacement with GGBFS in %	Compressive Strength in N/mm^2			Tensile Strength in N/mm^2		
		7 days	28 days	90 days	7 days	28 days	90 days
Mix I (0% RA)	0	28.50	53.71	59.65	2.72	4.69	5.2
	20	26.20	43.35	48.55	2.64	4.12	4.76
	30	23.60	40.40	49.86	2.49	3.84	4.8
	40	22.45	38.40	51.71	2.33	3.69	4.85
	50	20.65	36.10	48.20	2.21	3.56	4.78
Mix II (25% RA)	0	23.23	42.79	48.75	2.65	4.13	4.9
	20	23.2	39.2	44.20	2.52	3.65	4.3
	30	21.7	35.4	43.80	2.38	3.39	4.41
	40	20.2	34.8	46.34	2.22	3.19	4.54
	50	18.45	33.75	44.5	2.1	2.99	4.35
Mix III (50% RA)	0	22.24	39.72	44.76	2.31	3.72	4.48
	20	20.9	36	40.45	1.96	3.41	4.21
	30	20.4	34.9	40.9	1.8	3.14	4.25
	40	19.05	32.9	41.24	1.74	3.05	4.32
	50	17.1	31.65	40.6	1.63	2.84	4.24
Mix IV (100% RA)	0	19.91	33.78	39.55	2.01	3.21	4.02
	20	19.5	32.1	37.7	1.76	2.9	3.74
	30	19.3	29.5	37.2	1.72	2.78	3.82
	40	18.65	27.5	38.2	1.67	2.64	3.91
	50	15.2	26.35	36.95	1.54	2.59	3.78

Hence at 40% replacement level exhibits better pozzolanic action and fills the voids. Due to this modification of microstructures GGBFS concrete gives better strength. Therefore, 40% replacement of cement by GGBFS seems to be the better replacement. The result of present work also matches with results of earlier researchers [24].

b) Tensile strength

The indirect tensile test results of GGBFS based concrete for different percentage replacement of NA with RA are shown in Table 4. Similar trend as compressive strength was found in tensile strength of GGBFS-RAC as well. The tensile strength variation at the age of 28 and 90 days for mix I to IV for all cement replacements was shown in Fig. 7. From the results it is understood that the tensile strength of concrete reduced to the range of 12% to 25% in the earlier age (upto 28 days) irrespective of the replacement percentage (20% to 50%) of cement with GGBFS. However, the tensile strength of concrete improves when age increases and only lesser strength reduction value (6% to 8%) is observed in the later ages (90 days) of concrete, irrespective of the replacement percentage of cement with GGBFS. It is also observed that the strength improvement was reduced when GGBFS increased above 40% as replacement for cement in concrete. The same trend was observed for the NA with RA replaced concrete. For the mixes I to IV irrespective of replacements of NA with RA the tensile strength reduced to the range of 22% to 45%, when the percentage replacements of cement with GGBFS increased (20% to 50%). When the age of concrete increases the rate of strength gain also increases and the strength gain showed an ascending trend upto 40% cement replacement with GGBFS.

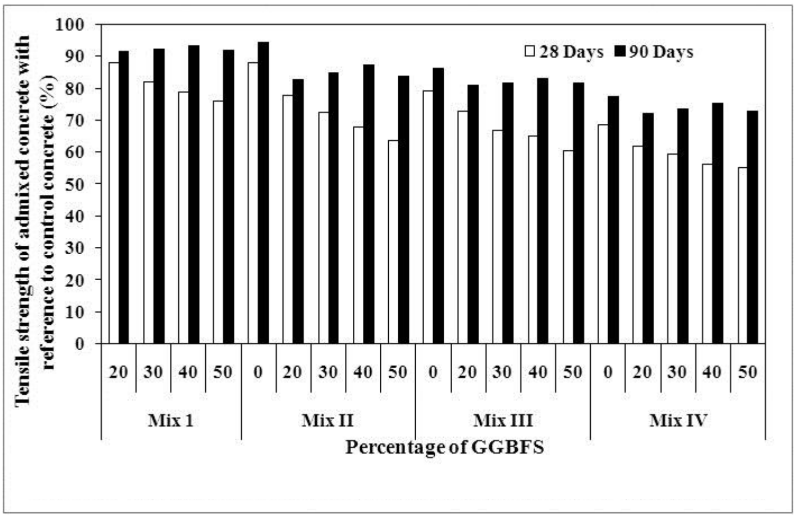

Fig. 7. Tensile strength of admixed concrete with reference to control concrete

Hence, from the above results it is understood that, the replacement of cement with 40% GGBFS is possible for all replacements of NA with RA. For replacement of NA with RA, 50% NA replacement gives around 40 MPa (75% of NAC strength) at the age of 28 days and in combination, 50% NA and 40% cement replacements with RA and GGBFS respectively gives around 61% of control concrete strength and hence it was selected as optimum mix proportion.

c) Resistance against capillary suction

The rate of capillary suction of hardened concrete for different combinations of cement and NA replacements are shown in Fig. 8. The cement with mineral admixture (GGBFS) replacement reduces the rate of capillary suction of RAC and improves the durability of RAC. The experimental results showed that the 100% replacement of RA in concrete without any mineral admixture increases the Sorptivity value by twice that of NAC and this water absorption can be reduced by replace cement with GGBFS to an extent of 50%. The RAC Sorptivity gets increased when the percentage of RA replacement in the concrete increases [25]. It was also reported that the RAC strength is affected if rate of water absorption was high and also the partial replacements of cement with admixtures significantly decrease the water absorption of RAC [26, 27]. The experimental results showed that the replacement of cement with GGBFS from 20% to 50% decreases the Sorptivity values in the range of 5% to 24% for NAC. Similar trend was also observed for RAC also. For 20% GGBFS concrete the rate of suction increases in the range of 13% to 83% for 25% to 100% RAC. Similarly for 30% GGBFS concrete it was 4% to 71%, for 40% GGBFS concrete it was 2% to 63%. For 50% GGBFS and 25% RA concrete the sorption characteristic improved by 6% compared with NAC. For 50% GGBFS and 100% RA concrete the difference was 47% higher than NAC. When RA was combined with GGBFS, improvement was observed in resistance to an extent of 21%, 24% and 27% for 25, 50 and 100% NA with RA replacements respectively.

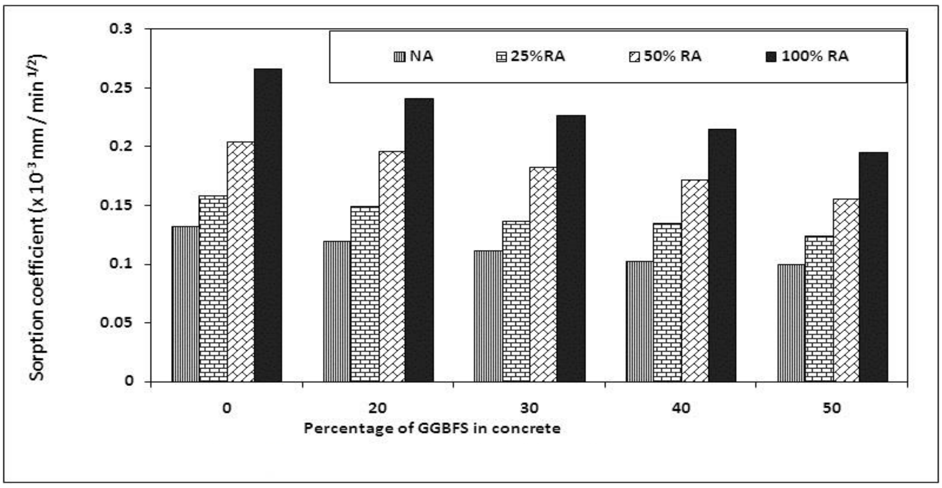

Fig. 8. Sorption coefficient of GGBFS-RAC

d) Resistance against chloride ion penetration

The experimental results of rapid chloride penetration test conducted on control specimen and specimens with RA and GGBFS are given in Fig. 9. The total charge passed (in Coulombs) through the RAC cylinder was greater than NAC cylinder which reflects the higher open pore structure of RAC than NAC. Hence, the chloride permeability increases with the increase in percentage replacement of RA. But with replacements of NA with RA in the range of 0 to 100%, the chloride ion penetration falls in the moderate range as per ASTM C1202 [22] guidelines and values were between 3078 to 3447 Coulombs. A slight increase in chloride ion penetration was observed when the RA content increased from 0% to 100% due to the porous nature of the RA [28]. The use of GGBFS as mineral admixture in concrete resulted in significant improvement in chloride ion penetration. The chloride ion penetration value for NAC reduced from 3078 to 2709 Coulombs for an increment of 20% to 50% GGBFS concrete. From the test results it was observed that concrete became significantly less permeable with increase in replacement of cement with GGBFS which in turn resulted in reduction in transport of chloride ion movement in concrete. Earlier researchers also reported that GGBFS in concrete was very effective to prevent the chloride ingress in concrete [29, 30, 31].

The same trend was observed for the concrete with 25% to 100% RA. One of the most important factors affecting the chloride ion penetration is permeability of concrete, which in turn is dependent on the extent of hydration of the cementitious materials. The amount of RA present in the concrete and the percentage replacement of cement with GGBFS of the concrete thus largely determine the ease with which chloride ions can move into concrete. The replacement of cement with admixture will produce higher amount of C-S-H gel during hydration and decrease the pore size and shapes, resulting in blocking diffusing path [32, 33]. For the RAC with GGBFS, the chloride ion penetration value is less than RAC without GGBFS and this decreasing trend will continue with higher replacements of cement with GGBFS. Hence it is concluded that GGBFS is more efficient in increasing the chloride penetration resistance of recycled aggregate concrete.

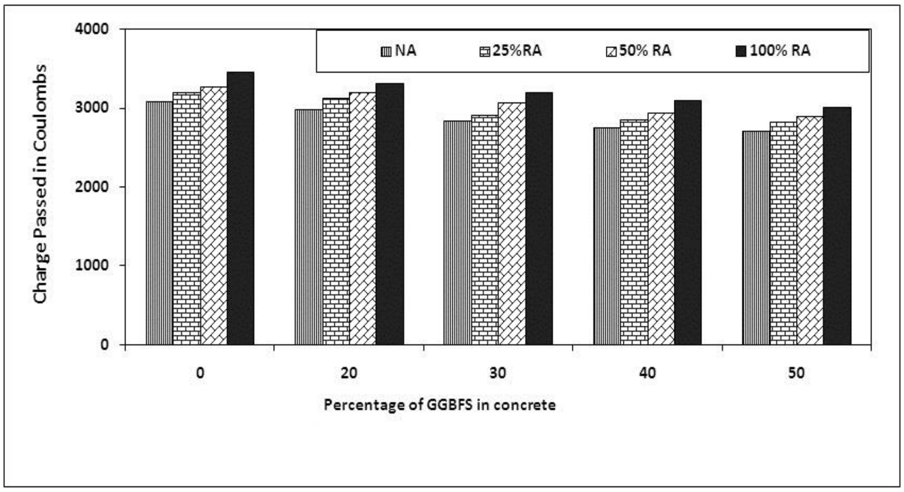

Fig. 9. RCPT values of GGBFC concrete

5. CONCLUSION

Based on the results of this experimental investigation conducted on recycled aggregate concrete with GGBFS, the following conclusions are drawn:

1. The compressive and tensile strength of admixed RAC has been found to be lower than the strength of NAC at all ages of concrete and for all percentage of NA and cement replacements.
2. At the age of 90 days the strength gain improves for concrete with more than 20% cement replacements with GGBFS than the concrete without GGBFS. The concrete with 40% GGBFS gives higher strength at the age of 90 days than other GGBFS based RAC mixes.
3. The rate of strength gain improves in the later age for the all replacements of NA with RA and cement with GGBFS. From the detailed study it was inferred that concrete with 40% GGBFS and 50% RA yielded better results compared to other combinations and was found to be optimum. Hence it can easily be tried in the field.
4. The resistance against sorption for RAC was less compared to NAC. Whereas when RAC combined with GGBFS, the improvement in resistance against sorption was in the range of 21%, 24% and 27% for 25, 50 and 100% NA with RA replacements respectively.
5. Similarly when RA was combined with GGBFS, maximum resistance against chloride ion penetration was observed at higher replacement (50%) of cement with GGBFS to an extent of 12% for 25 to 100% NA replacements.

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