Indian Journal of Engineering & Materials Sciences
Vol. 31, August 2024, pp. 547-559
DOI: 10.56042/ijems.v31i4.5708

Investigation of the performance of brick aggregate concrete incorporating rice husk ash in the corrosive environment

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Received: 21 September 2023; Accepted: 11 March 2024

Brick aggregate concrete (BAC) is susceptible to rebar corrosion due to its porous nature. Rice husk ash (RHA) has the potential to improve a few properties of concrete by replacing ordinary Portland cement (OPC) including porosity and permeability. In this experimental work, BAC samples with different percentages of RHA have been cast and exposed to corrosive mediums such as concentrated chloride and concentrated carbon-di-oxide environments. The periodic observations in terms of non-destructive tests such as the half-cell potential test and resistivity test have been conducted to measure the probable chloride-induced corrosion that occurred in the specimens. The samples were also kept exposed to the concentrated CO_2 medium and subjected to periodic carbonation depth teststo monitor the CO_2 penetration into the concrete samples. Additionally, sorptivity and permeability tests have been conducted on concrete specimens to reveal the effectiveness of RHA in reducing the porosity and permeability of concrete. In the experimental studies, 5% RHA was proven to be optimum for the lower w/b ratio and 10% RHA was proven to be optimum for the higher w/b ratios in chloride-induced corrosion as well as carbonation depth test. Finally, the correlation between the non-destructive methods and the degree of corrosion of the rebar has been established from the values of the experimental studies.

Keywords: Rice husk ash, Chloride induced corrosion, Carbonation depth, Half cell potential, Resistivity

1 Introduction

Corrosion of reinforcing steel bars (rebar) in concrete is a determining factor for the service life of an RCC structure. Steel bars embedded in concrete are immune to corrosion due to the alkalinity of the concrete interior. However, due to a few environmental factors, the alkalinity inside the concrete is reduced and corrosion of rebar is initiated. Accumulation of chloride ions and carbon dioxide are among the most common causes of the reduction of the alkalinity of concrete thereby resulting in rebar corrosion.

In many areas of the world use of alternative coarse aggregate becomes obvious due to the inadequate supply of natural granite. Brick aggregate has been used as an alternative to stone aggregate in concrete in many areas including some parts of India and Bangladesh[1].This practice of using brick aggregate yields concrete with decent strength which is adequate for the construction of a normal structure. Dey and Pal and Rashid *et al*. obtained more than 40 MPa strength using 100% Brick aggregate concrete[1,2]. However, compared to stone aggregate concrete brick aggregate (BAC) concrete is still weaker and less durable. Khalaf and Devenny observed a 19 to 20 % reduction in the strength when brick aggregate is used instead of stone aggregate in concrete[3]. A greater reduction of 33% and 43% was observed by Rashid *et al*. and Lonth *et al*.[4,5]. The porosity of (BAC) has been observed to be quite higher than that of stone aggregate concrete. Aliabdo *et al*. observed 3 to 5 times greater water absorption (indirect measurement of porosity) in Brick aggregate concrete than the conventional stone aggregate concrete[6]. The higher porosity of brick aggregate concrete was also observed in the sorptivity test carried out by Akhter *et al*.[7]. The greater porosity of the brick aggregate concrete makes it more permeable than conventional stone aggregate concrete as can be seen in the findings of Ahmad *et al*.[8]. The porous and permeable nature of BAC makes it susceptible to the corrosion of reinforcing steel bars. Pashupathy *et al*. studied the porosity and permeability of the concrete samples along with the chloride and carbonation penetration tests. It was observed that the concrete samples with more permeability have lower resistance to chloride, carbonation, and other aggressive mediums[9]. Mohammad *et al*. and Baten *et al*. have also concluded that brick aggregate concrete is more vulnerable to rebar corrosion than standard stone aggregate concrete[10,11].

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The use of supplementary cementitious material (SCM) has several benefits to concrete. Sometimes the use of SCM can make concrete more resistant to rebar corrosion. Monticelli *et al*. found alkali-activated fly ash mortar to be more resistant to chloride environment than OPC mortar[12]. However, the application of different types of SCM can have a different effect on the concrete samples. Babae and Castle experimented with fly ash-based geo-polymer concrete (GPC) and no significant improvement was found in resisting chloride-induced corrosion[13]. Pashupathy *et al*. found fly ash-based GPC to be inferior to the control concrete in resisting chloride-induced corrosion[9].Hossain and Lachemi observed an improvement in the corrosion behavior of concrete after adding volcanic ash to concrete as an SCM[14].Yeau and Kim studied the corrosion behavior of concrete with ground granulated blast furnace slag (GGBS). It was observed that GGBS improved the resistance to corrosion of reinforcing bars in concrete[15]. Rice husk ash (RHA) is a supplementary cementitious material and it has been proven to be efficient in reducing chloride penetration in stone aggregate concrete[16-22]. RHA is mainly consisting of silica and possesses pozzolanic properties. This material has the potential to improve the strength and durability of the concrete specimen and has been studied by many researchers[16-25]. The application of RHA in brick aggregate concrete has been studied very little. Noaman *et al*., Noaman *et al*. and Bhowmik and Pal studied the strength and durability of brick aggregate concrete incorporating RHA[23-25]. Bhowmik and Pal observed that the application of RHA has more impact on the brick aggregate concrete than the corresponding stone aggregate concrete as the filler effect of RHA has more scope to improve comparatively more porous brick aggregate concrete[25]. However, there are still a few research gaps in the study of the application of RHA in BAC. The performance of brick aggregate concrete incorporating RHA in corrosive mediums such as concentrated chloride solution and concentrated carbon-di-oxide environment is yet to be studied.

In this experimental work, BAC samples with different percentages of RHA have been cast and exposed to concentrated chloride and concentrated carbon-di-oxide environments. The periodic observation in terms of the Half-cell potential (HCP) test and resistivity test has been conducted to measure the probable chloride-induced corrosion that occurred in the specimens. The samples exposed to the concentrated CO_2 medium were subjected to a carbonation depth test to monitor the CO_2 penetration into the concrete samples. Additionally, sorptivity and permeability tests have been conducted on concrete specimens to reveal the effectiveness of RHA in reducing the porosity and permeability of concrete. Later on, the correlation among HCP, resistivity, and actual damage due to corrosion is established.

2 Materials and Methods

2.1 Materials

The concrete samples were made of ordinary Portland cement(OPC-43 grade). The properties of the cement are presented in Table 1. Cement replacement

Table 1 — Properties of materials used in this study.

	RHA	Cement	Brick aggregate	Stone aggregate	sand
Specific gravity	2.2	3.05	2.1	2.62	2.55
Colour	grey	grey	red	Grey	white
Blain's permeability	4200 cm^2/g	3210 cm^2/g	-	-	-
Water absorption (24 hr)			15.3%	1.7%	2.6%
Nominal size			15 mm	15 mm	Zone IV (IS 383)
Oxide composition by XRF test					
SiO_2	96.7	21.53			
Al_2O_3	0.31	6.89			
Fe_2O_3(T)	0.17	2.92			
MnO	0.119	0.007			
MgO	0.35	2.85			
CaO	0.39	58.56			
Na_2O	0	0.78			
K_2O	1.17	0.47			
TiO_2	0	0.41			
P_2O_5	0.54	0			
SO_3	0.11	5.23			

was done using RHA collected from a local rice mill situated in Tripura, a northeastern province of India. From Table 1 it can be seen that RHA is substantially lighter than cement and it contains mainly silica. The X-Ray Diffraction (XRD) curve of the RHA shows a hump rather than a sharp peak which reveals the presence of amorphous silica, Figure 1. Brick aggregate is collected from local brick industries of Jirania, Tripura. Fine aggregate is collected from the Howrah river bed of Tripura. The properties of the brick aggregate, stone aggregate, and fine aggregate are presented in Table 1.

2.2 Samples description

The samples were prepared using three different w/b ratios such as 0.38, 0.46, and 0.54. The percentage of RHA varied in the range of 0 to 20%. The mix proportion of the concrete samples is presented in Table 2. The mix calculation has been done with the help of IS:456.2000[26], IS 10262[27], and IS 383[28].

2.3 Sorptivity test

The sorptivity test was conducted to evaluate the porosity of the concrete samples. The oven-dried cylindrical concrete samples of length 50 mm and diameter 100 mm were placed in such a manner that one plane surface of the concrete sample touches the water surface, Fig. 2. Water is allowed to enter into the concrete samples employing capillary actionon that surface only and other air-exposed parts were coated with epoxy. The quantity of the absorbed water is calculated by subtracting the dry weight of the samples from the present weight. The sorptivity was calculated using Equation 1. The test procedure follows ASTMC1585-20[29].

$$I = \frac{Q}{A} \quad \text{... (1)}$$

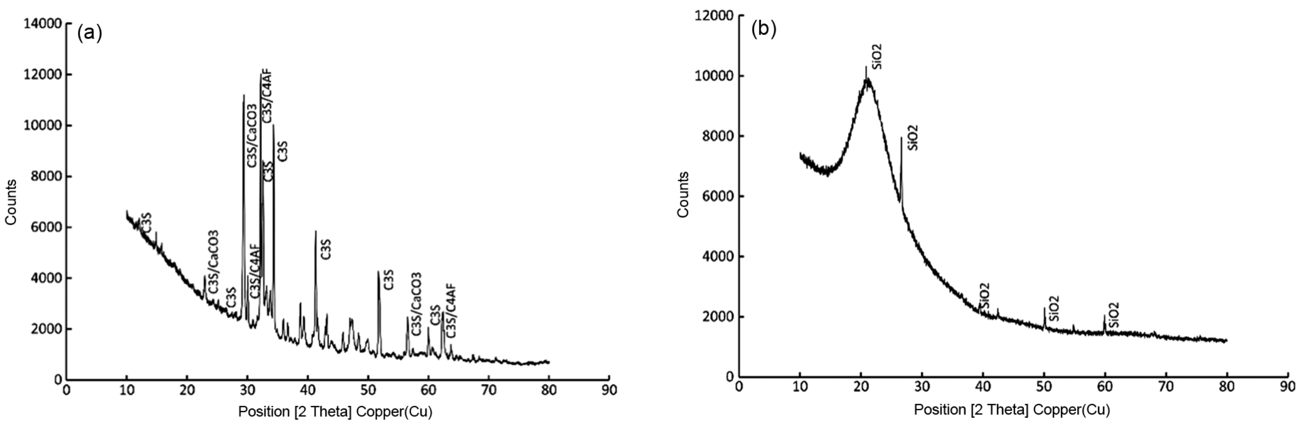

Fig. 1 — (a) XRD of OPC, and (b) XRD of RHA.

Table 2 — Concrete mix proportions for different specimens.

Sl	w/b	%RHA	Cement	RHA	water	C/A	F/A
			BAC and RHA-BAC specimens				
M1	0.38	0	420	0	159.6	968.83	606.04
M2	0.38	5	399	21	159.6	965.14	603.74
M3	0.38	10	378	42	159.6	961.45	601.43
M4	0.38	15	357	63	159.6	957.77	599.12
M5	0.38	20	336	84	159.6	954.08	596.82
M11	0.46	0	420	0	193.2	922.26	576.91
M12	0.46	5	399	21	193.2	918.57	574.60
M13	0.46	10	378	42	193.2	914.89	572.30
M14	0.46	15	357	63	193.2	911.20	569.99
M15	0.46	20	336	84	193.2	907.51	567.69
M21	0.54	0	420	0	226.8	875.69	547.78
M22	0.54	5	399	21	226.8	872.00	545.47
M23	0.54	10	378	42	226.8	868.32	543.17
M24	0.54	15	357	63	226.8	864.63	540.86
M25	0.54	20	336	84	226.8	860.94	538.55

C/A= Coarse Aggregate; F/A = Fine Aggregate; and w/b = water to binder ratio

Fig. 2 — Sorptivity test setup.

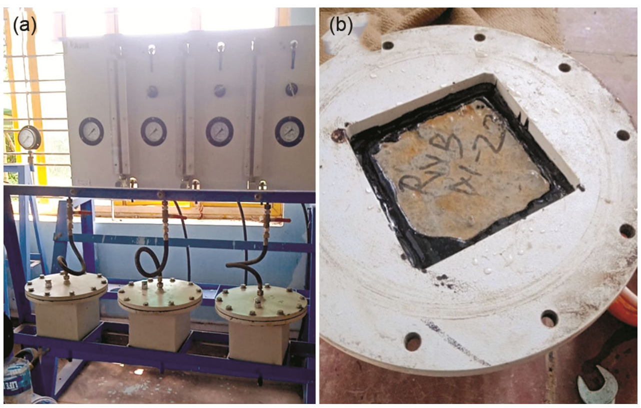

Fig. 3 — (a) Permeability test setup, and (b) concrete cube in permeability chamber after sealing.

$$I = A + S\sqrt{t} \quad \text{... (2)}$$

Where I = cumulative capillary absorption in mm, Q = volume of the absorbed water in mm^3, A = area of the samples in mm^2, and t= time in second after the commencement of the test, S= Coefficient of sorptivity.

2.4 Permeability test

To conduct the test,100 mm cube samples were placed in the permeability cell and the lateral surfaces were sealed with wax and bitumen as shown in Fig. 3. Water at a pressure of 10 N/cm^2 was applied on the top surface of the cube. Due to the highpressure water penetrates the concrete cube and comes out from the bottom surface. This water was collected in the container for 48 hours and measured. The co-efficient of the permeability was evaluated with the help of Equation 3. The test procedures follow the guidelines mentioned in BIS:3085[30].

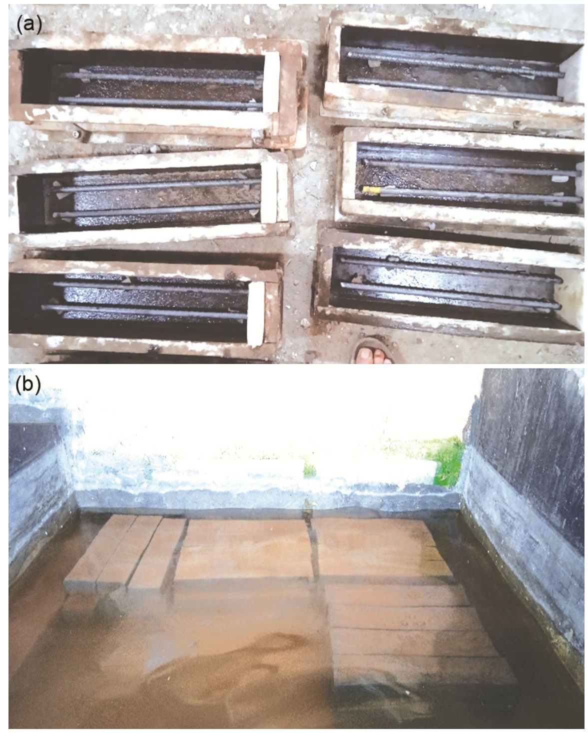

Fig. 4 — (a) formwork for RCC beam. (b) beam samples in the curing tank.

$$K = \frac{Q}{A.T.h/L} \quad \text{... (3)}$$

Where K = coefficient of permeability; Q = volume of water collected in ml; A= Area of the sample exposed to water head; T= time in seconds; h = pressure head in cm, L= length of the specimen in cm.

2.5 Exposure to concentrated chloride environment

Concrete beams of size 100 mm x 100 mm x 450 mm were submerged under 5% NaCl solution in a curing tank for 360 days along with periodic drying and wetting cycles. Feng *et al*. reviewed many studies regarding the acceleration of chloride-induced corrosion and found many authors used a 5% NaCl solution for the acceleration of chloride-induced corrosion[31]. Beam samples were reinforced with 2 nos 12 mm dia bar with 15 mm clear cover. The formwork of the beam with centering is shown in Fig. 4(a). One end of the rebars was kept exposed (concrete-free) to conduct the HCP test. during chloride exposure, the exposed portion of the steel rebars was covered with grease to avoiddirect contact with the chloride solution. Figure 4(a) presents the formwork for the concrete samples beforecasting. Figure 4(b) shows the samples under the curing tank. Figure 5(a) shows the samples under NaCl solution

Fig. 5 — (a) beam samples in 5% NaCl solution, and (b) drying phase.

(wetting cycle). Figure 5b shows the beam samples in the drying phase.

2.6 Half-cell potential test

HCP test is a reliable nondestructive method for the evaluation of the corrosion of reinforcement bars. The test instrument consists of two electrodes and a half-cell. The reference portable electrode is in contact with the concrete specimen and another electrode is connected to the exposed rebar as shown in Fig. 6(a). The half-cell is made up ofa copper sulfate solution ($CuSO_4$) filled tube, a copper rod, and a porous wooden plug. the potential difference between two electrodes is measured with a high impedance volt-meter. The potential difference indicates the probability of the occurrence of the corrosion of the rebar. The test procedure is described in ASTM C876[32].

HCP test has been carried out on the RCC beams (which were exposed to chloride concentrated medium mentioned earlier in 2.5) at regular intervals of 30 days for an extended period of 180 days. After 180 days the test was conducted at an interval of 60 days and continued up to 360 days. The readings were taken at different points on the cover of the test beam as shown in Figure 6b. The longitudinal lines indicate the location of the steel bars and the lateral lines are

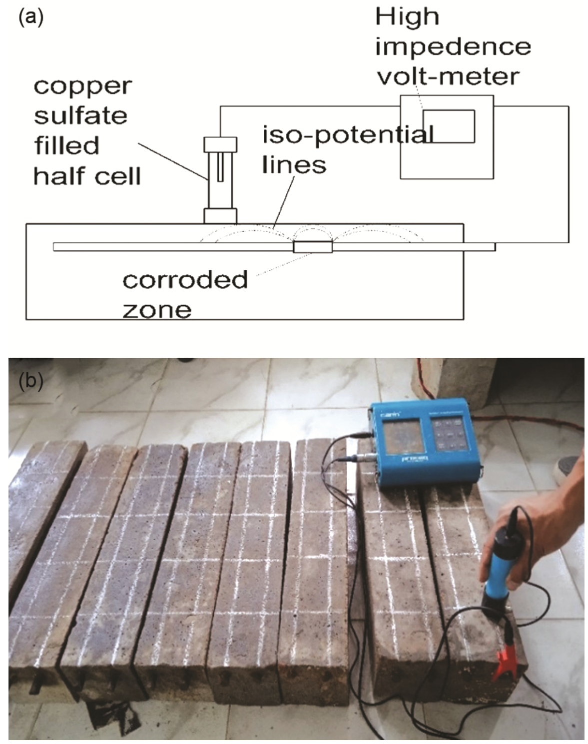

Fig. 6 — (a) Schematic diagram of Half-cell potential test, and (b) Half-cell potential test on the RCC beam samples.

drawn at 10-cm intervals to mark the location of the reading. The average of all the readings is taken as the overall HCP value of a beam after a certain chloride exposure period. The instrument and test setup are presented in Fig. 6(b).

2.7 Resistivity test

The value of the resistivity test indicates the chloride ion ingress into the concrete cover. The test is conducted using a volt meter and a Wenner probe. The Wenner probe consists of four electrodes that are in contact with the concrete surface as shown in Fig. 7(a). The electrodes at the two ends are used for the current measurement and the electrodes positioned in the middle are used for the measurement of the potential. The digital unit provides the resistivity of the concrete by using the potential and current measurements. The procedure follows the guidelines provided in AASHTO TP 95[33].

The resistivity test had been carried out on the RCC beam samples periodically for an extended period of 360 the same way the HCP test had been conducted. The test was carried out on the different locations of the cover of the RCC beam with a spacing of 150 cm. The Wenner probe was also placed in such a way that it did not coincide

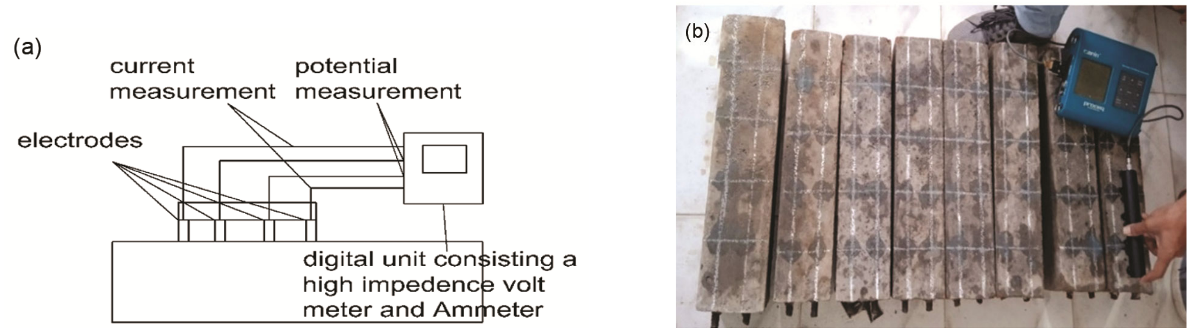

Fig. 7 — (a) Schematic diagram of resistivity test, and (b) resistivity test on the RCC beam samples.

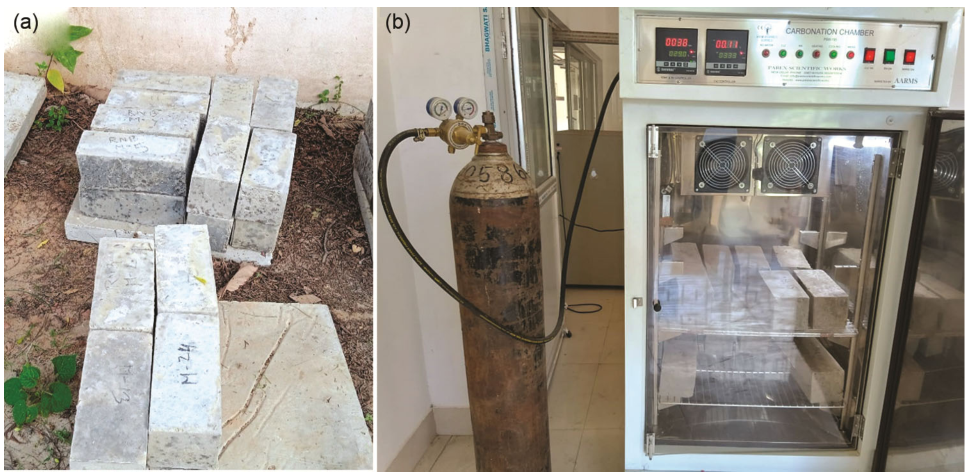

Fig. 8 — (a) samples for carbonation depth test, and (b) samples in the carbonation chamber.

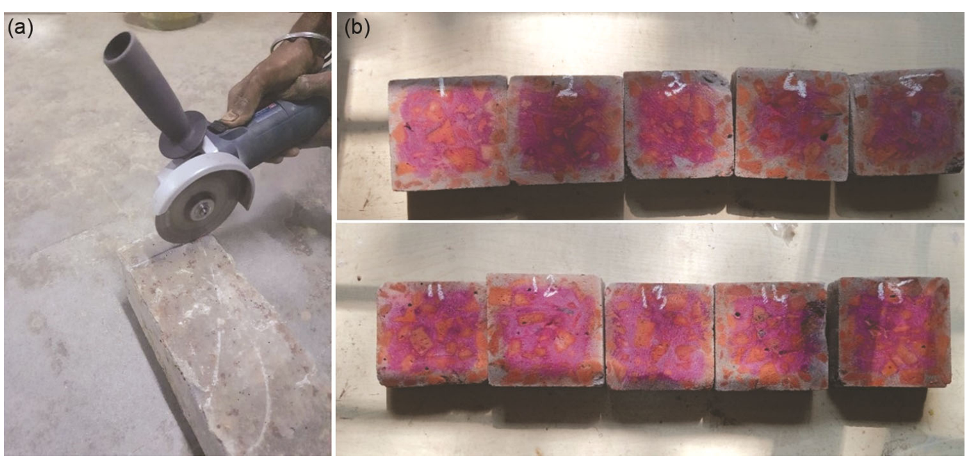

Fig. 9 — (a) cutting of concrete sample to obtain fresh section, and (b) concrete section tested for carbonation depth by the application of the indicator.

with the steel bar line. The test setup is presented in Fig. 7(b).

2.8 Carbonation depth test

Concrete samples of size 100 mm x 100 mm x 250 mm were cast to conduct the carbonation test as shown in Fig. 8(a). The test samples were kept in the carbonation chamber for 360 days at 3.33% CO2 concentration as shown in Fig. 8(b).The carbonation depth was observed by applying a phenolphthalein indicator on the fresh cross-section obtained after the cutting of the specimen as shown in Fig. 9. The carbonation depth test was conducted at 90 days intervals and continued for 360 days. The indicator shows purple color if the concrete is not carbonated and becomes colorless when applied to a carbonated portion (Fig. 9). The depth of the carbonation front was measured along the circumference of the concrete section at various points and the average carbonation depth was calculated.

3 Results and Discussion

3.1 Results of the sorptivity test and permeability test

The results of the sorptivity are presented as the coefficient of sorptivity in Fig. 12. The test values of the coefficient of the sorptivity indicate the surface porosity of the corresponding concrete sample. The increasing trend of the value can be observed with the increasing w/b ratio. The value of the coefficient of sorptivity of control brick aggregate concrete was found to be 0.0142 to 0.0195 $cm/s^{0.5}$. The performance of the RHA-added concrete was found to be better than that of the control concrete in most cases. Especially 5% and 10% RHA samples had performed significantly better than the corresponding control concrete. in 0.38 w/b ratio 15% and 20% RHA has coefficient permeability greater than control concrete of the same grade. In the case of 0.46 w/b ratio, the test result of the 15% samples was comparable to that of control concrete but 20% RHA samples have significantly higher values. In the case of 0.54 w/b ratio 0-15% RHA samples performed better than the control concrete however the value of the 20% RHA sample is still higher than that of the control concrete. From Fig. 10 it can be observed the optimum RHA percentage is 10% for the sorptivity test. At optimum RHA% 16.5 to 31.8% improvement can be observed over control brick aggregate concrete. However, 15% RHA also can be used as the values are very much similar to control concrete.

The result of the permeability test is shown in Fig. 11 as the coefficient of permeability. Similar to the sorptivity, permeability also increases with the increase in the w/b ratio. Control concrete has a coefficient of permeability of 4.05 x 10^{-9} to 6.5 x10^{-9} cm/s. In the permeability test, 5% and 10% RHA samples performed better than the control concrete in the case of all w/b ratios. coefficient of the permeability of 15% RHA samples is higher than the control concrete in 0.38 w/b ratio. However, in the 0.46 and 0.54 w/b ratios the value is lower than that of control concrete. the coefficient of permeability of 20% RHA samples was observed to be quite higher than that of control concrete in a low w/b ratio such as 0.38 where the value is 58.5% greater than that of control concrete. However, in the 0.46 w/b ratio the performance of the 20% RHA sample is much closer to the control concrete and the difference is only 12%. In the case of a 0.54 w/b ratio, the performance of the 20% samples was marginally better than that of control concrete. The optimum percentage of RHA was found to be 5% for the 0.38 w/b ratio and 10% for the other w/b ratios. the reduction in the coefficient of permeability at the optimum w/b ratio was observed to be 17.1% to 31.1%.

3.2 Results of the HCP test

The values of the Half-cell potential (HCP) decrease as the exposure time increases as the accumulation of chloride ions increases the

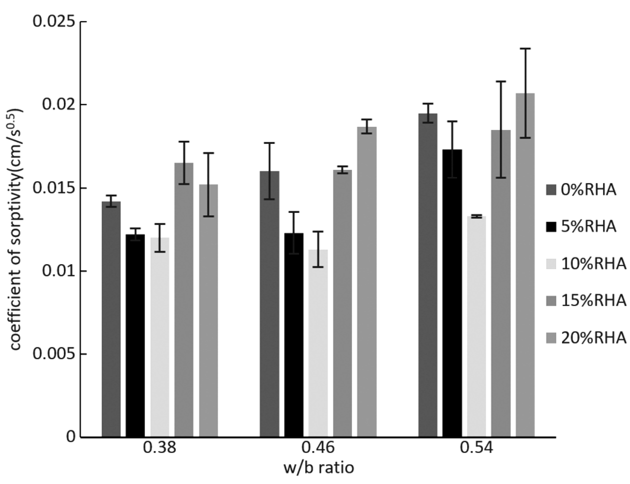

Fig. 10 — the co-efficient of sorptivity of different concrete specimens.

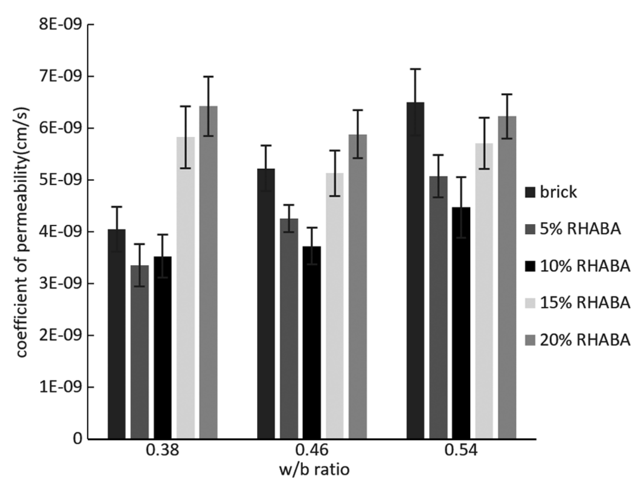

Fig. 11 — coefficient of permeability of different concrete mixes.

probability of corrosion of the steel rebars. Initially, the values of HCP are in the range of 50 to 150 mV. After 60- 120 days a sudden decrease in the potential can be seen after a period (Figs 12-14). This sudden fall in the half-cell potential value indicates the de-passivation stage[34]. After the de-passivation stage corrosion takes place rapidly. Figure 12 illustrates the HCP value of the concrete samples with a 0.38 w/b ratio. The de-passivation of control concrete witha 0.38 w/b ratio started to occur between 90 to 120 days. In the concrete sample of 5% RHA with the same w/b ratio, de-passivation starts after 120 days.In terms of HCP values, the 5% RHA samples performed better than the control concrete of the same w/b ratio. The de-passivation of 10% RHA samples also started after 90 days which is similar to the control concrete but in the case of 10% RHA samples, the HCP values are marginally lower than that of control concrete. The de-passivation of 15% and 20% RHA samples started between 60 to 90 days which is comparatively earlier than the other samples of the same grade. In terms of HCP values, the performance of these samples is also lower than the other samples of the same grade. Figure 13 shows the graphical representation of the HCP values of the samples with a 0.46 w/b ratio. The de-passivation of control concrete and 5% RHA samples starts after 90 days whereas, in the case of 10% RHA samples,the de-passivation stage came after 120 days. In terms of HCP values, both 5% and 10% RHA samples performed significantly better than the control concrete. The depassivation stage of 15% and 20% of samples came in between 60 to 90 days. However, the HCP values of 15% RHA are closer and comparable to that of control concrete whereas the performance of 20% RHA is significantly worse than the control concrete. The HCP values of 0.54 w/b ratio samples are shown in Fig. 14. A igher w/b ratio causes a relatively earlier occurrence of de-passivation. The control concrete undergoes de-passivation after 60 days of exposure. Similar to 0.46 w/b, in the case of w/b ratio 0.54, 10% RHA samples had the best performance both in terms of HCP values as well as the occurrence of the de-passivation. In the case of both 5% and 15% RHA samples de-passivation starts within 60-90 days. HCP values of the 5% RHA samples are higher than the control concrete. The performance of 15% RHA samples is better than control concrete according to HCP values up to 180 days. However, after 180 days control concrete performed better. The introduction of the de-passivation of 20% RHA samples starts at 60 days which is similar to the control concrete. However, the HCP values are much lower compared to the control concrete.

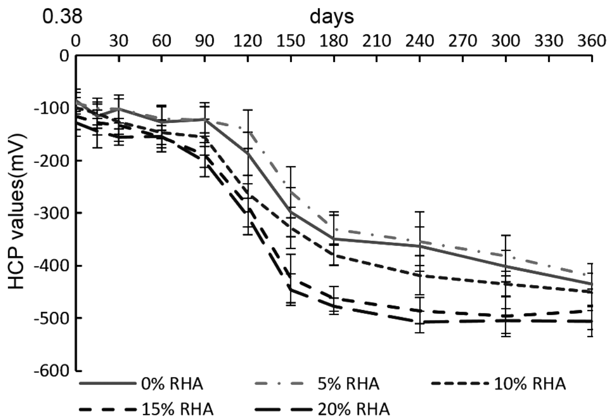

Fig. 12 — Overall HCP test values for the beam samples for w/b 0.38.

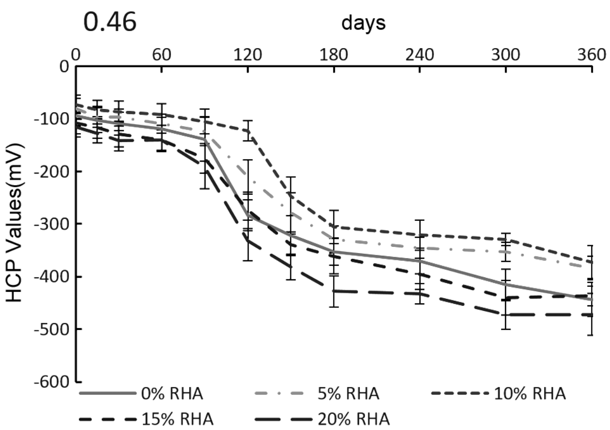

Fig. 13 — Overall HCP test values for the beam samples for w/b 0.46.

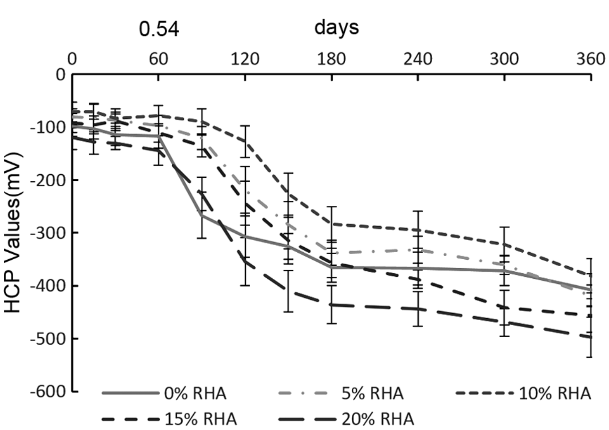

Fig. 14 — Overall HCP test values for the beam samples for w/b 0.54.

3.3 Results of the resistivity test

The resistivity values of the samples before exposure to chloride solution were found to be 35 to 40 kOhm. The resistivity after 360 days was found to be in the range of 7 to 20 kOhm as shown in Figs 15-17. It can be observed that with different w/b ratios, the initial values resistivity remains in the same range. However, the higher w/b ratio samples tend to yield comparatively lower resistivity in the later stage of the experiment as shown in Figs 15-17. Figure 15 shows the results of the resistivity test of the 0.38 w/b samples. The initial values of control concrete, 5% RHA, and 10% RHA samples are 39.28, 40.05, and 39.76 kOhm which are very close and comparable. The Final values of resistivity after 360 days can be observed that 5% RHA samples perform significantly better than control concrete in the w/b ratio of 0.38. The performance of 10%, 15%, and 20% remains below the control concrete. The observation is also in agreement with the result of the HCP test and permeability test. Figure 16 illustrates the resistivity values of the samples of 0.46 w/b ratio. The concrete samples with 10% RHA show the highest resistivity value after 360 days. The 5% RHA sample also performed better than the control concrete. In the case of 15% and 20% RHA samples, resistivity values after 360 days were lower than control concrete. Figure 17 presents the values of the resistivity test on the samples of 0.54 w/b ratio. Similar to the 0.46 w/b ratio, in the 0.54 w/b ratio, the concrete samples with 5% and 10% RHA performed better than the control concrete. The performance of 15% and 20% RHA samples was not as good as the control concrete.

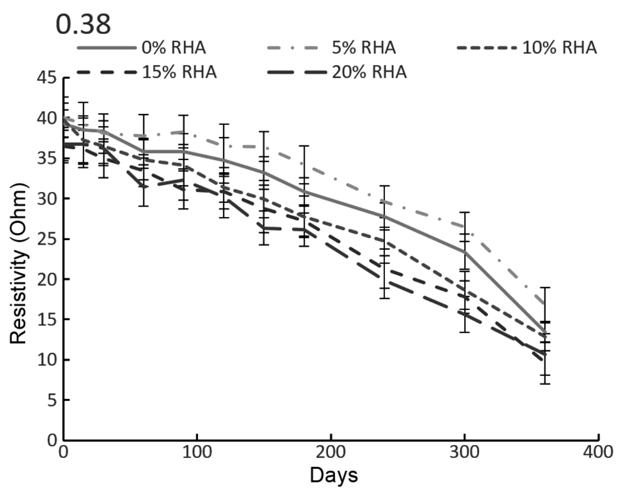

Fig. 15 — overall resistivity test values for the beam samples for w/b 0.38.

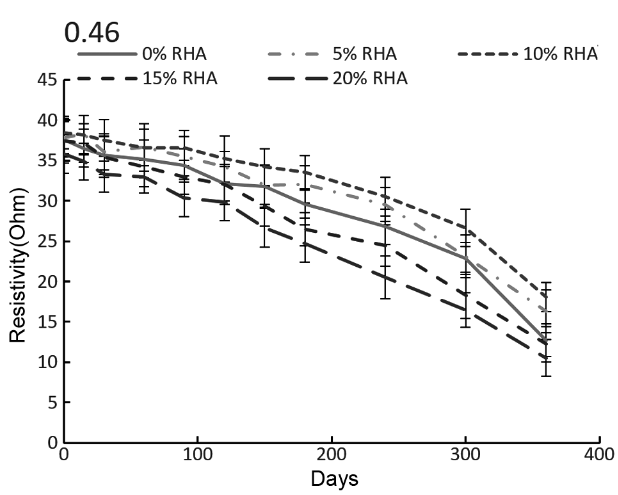

Fig. 16 — overall resistivity test values for the beam samples for w/b 0.46.

3.4 Mass loss of rebars

To find the actual corrosion of the reinforcement bars concrete samples were demolished after 360 days and steel bars were collected for further investigation as shown in Fig. 18. The rust in the steel bars was removed using diluted hydrochloric acid as mentioned in Thapa *et al.* [34]. The steel bars are then weighed and compared to the initial mass to obtain the mass loss percentage. The mass loss of the reinforcement bars was found to be in the range of 10 to 17% of the initial weight. The mass loss of the control brick aggregate concrete is in the range of 12.33 to 14.25 % as shown in Fig. 19. The lowest mass is observed with 5% RHA in a 0.38 w/b ratio. However, in 0.46 and 0.54 w/b ratio 10% RHA samples undergoes the lowest mass loss. The result of the mass loss is in

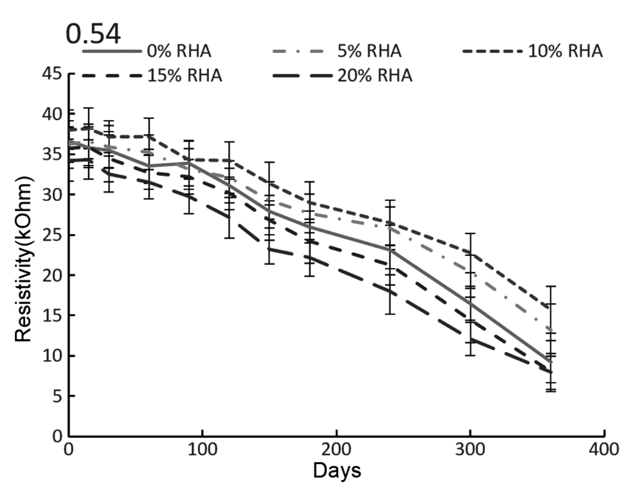

Fig 17 — Overall resistivity test values for the beam samples w/b 0.54.

Fig. 18 — (a) Half demolished RCC beams after 360 days of NaCL exposeure, and (b) corroded reinforcement bar extracted from RCC beams.

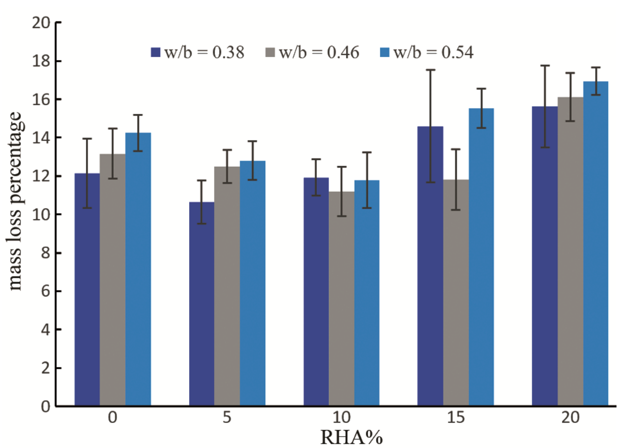

Fig. 19 — Mass loss of the reinforcement bars after 360 days.

good agreement with the results of HCP and resistivity tests.

3.5 Correlation between average mass loss of rebars overall HCP values and resistivity values

The non-destructive methods such as HCP and resistivity test can be more utilized in the field of structural health monitoring if a good correlation

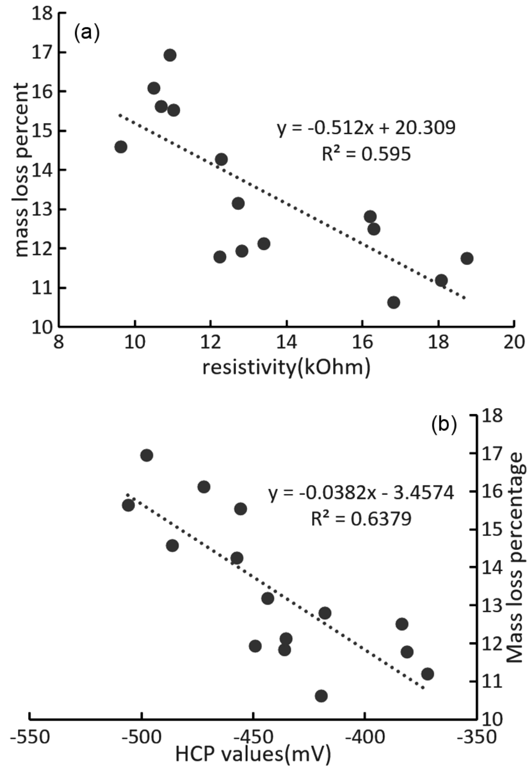

Fig. 20 — (a) Mass loss of rebar vs resistivity curve, and (b) Mass loss of rebar and HCP curve.

exists with the actual values. Although the correlation already has been made earlier, still some gaps arise with the newer unconventional materials such as brick aggregate and RHA. In this section, the HCP values and resistivity values are compared with the mass-loss percentage using the linear regression method. Figure 20 shows the graph between actual mass loss and non-destructive test methods. It can be seen that a good correlation exists between the actual mass loss of the steel rebars and non-destructive test values. The correlation between resistivity and mass loss has an R-square value of 0.595 whereas the correlation between HCP and mass loss possesses a higher R-square value of 0.64. Table 3 shows the equations of correlation with standard errors and R-square values for different variables. A multivariable correlation is also presented in Table 3 that can be used to predict the mass loss of rebar using both HCP and resistivity values. Figure 21 shows the comparison between predicted values of mass loss from the multivariable equation and the experimental values of mass loss.

3.6 Results of the carbonation depth test

Carbon dioxide penetrates the concrete cover and reduces the alkalinity of the concrete. The exposure to

Table 3 —Results of the linear regression correlation taking HCP and resistivity as input and the mass loss percentage of rebar after 360 days.

	Equation	R-square	Standard error	No of data
Single variable (HCP)	Mass loss = -0.0382HCP - 3.4574	0.638	1.23	15
Single variable(resistivity)	Mass loss = -0.512Res + 20.309	0.595	1.3	15
Two variables	3.05717-0.0281HCP-0.152Res	0.646	1.266	15

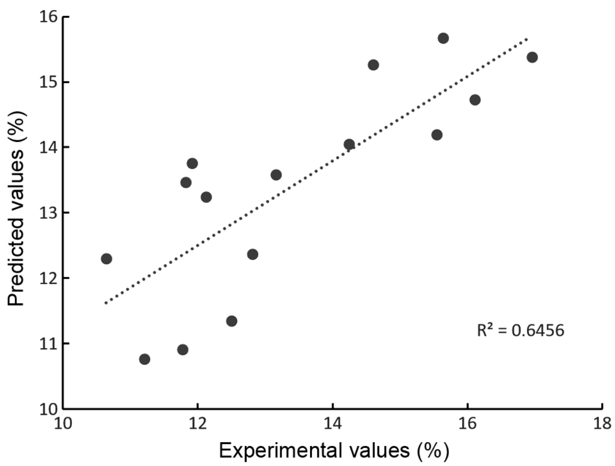

Fig. 21 — Experimented with mass loss vs predicted values of mass loss by a two-variable equation.

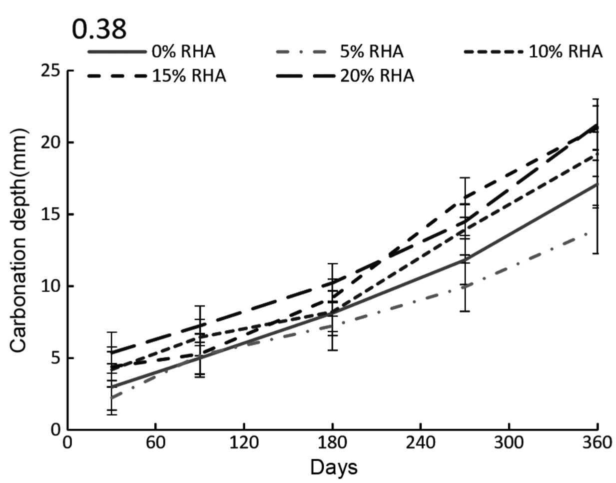

Fig. 22 — Carbonation depth for the beam samples for w/b 0.38.

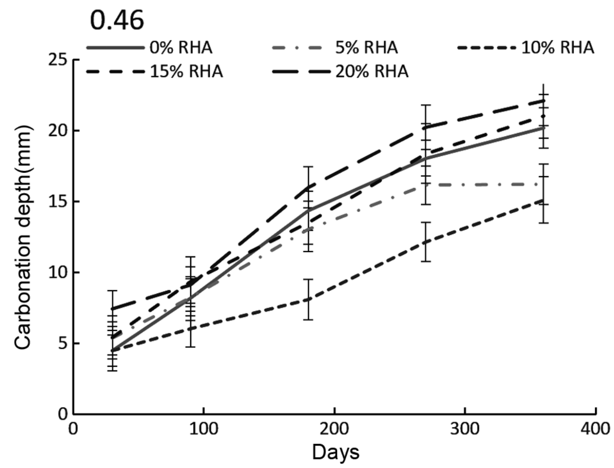

Fig. 23— Carbonation depth for the beam samples for w/b 0.46.

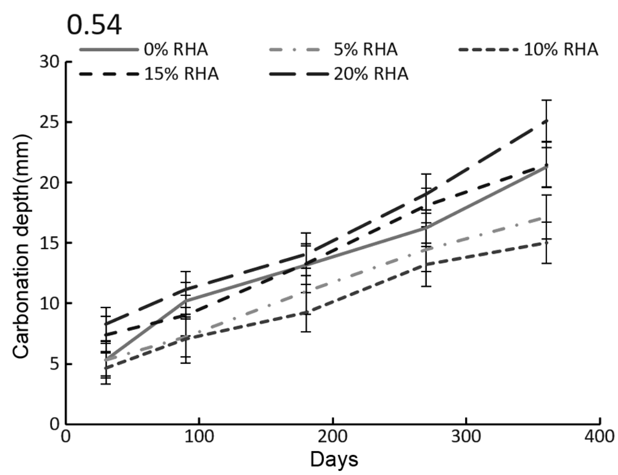

Fig. 24 — Carbonation depth for the beam samples for w/b 0.54.

360 days of 3% CO_2 environment causes accelerated penetration of CO2 into the concrete. The control concrete of 0.38 w/b ratio got a carbonation depth of 17 mm after 360 days as shown in Fig. 22. The concrete samples with 5% RHA show much lower carbonation depth after 360 days exposure period, which is 19% less than the control concrete. 10% RHA sample shows carbonation depth similar to control concrete up to 180 days. however, after 360 days carbonation depth of 10% RHA samples is 12% more than that of control concrete. much higher carbonation depth is observed in the case of 15% and 20% RHA. Figure 23 shows the carbonation depth values of the concrete samples of 0.46 w/b ratio. The control concrete shows a carbonation depth of 20.16 mm after 360 days of exposure. 5% and 10% RHA samples performed better than the control concrete. with 5% RHA 19.6% and with 10% RHA 25.6% reduction in the carbonation depth can be observed. The performance of 15% RHA is very much similar to the performance of control concrete. the concrete with 15% RHA shows 4.1% more carbonation depth than the control concrete after 360 days. Figure 24 shows the results of the carbonation depth

Table 4 — Results of the linear regression correlation taking the coefficient of permeability and coefficient of sorptivity as input and the carbonation depth after 360 days.

	Equation	R-square	Standard error
Single variable (sorptivity)	CD=884.25 S+5.3538	0.679	1.884
Single variable(permeability)	$CD= 2*10^9 P+6.728$	0.68	1.879
Two variables	$CD =5.107337+470.2824S+1.33*10^9P$	0.728	1.803

Where CD= carbonation depth; P= coefficient of permeability; S= coefficient of sorptivity

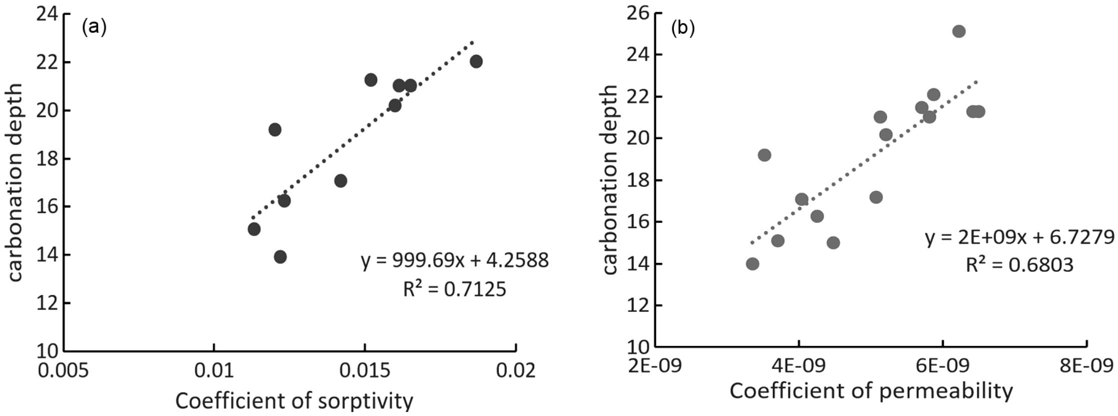

Fig. 25 — (a) Carbonation depth vs coefficient of sorptivity, and (b) Carbonation depth vs coefficient of permeability.

test of 0.54 w/b ratio. The carbonation depth of the control concrete was observed to be 21.475 mm. The carbonation depth observed in the 5% RHA samples was 18.5% less and the carbonation depth of the 10% samples was 30.30 less than the control concrete. the performance of 15% RHA samples was close and comparable to that of control concrete and 20% RHA samples achieved 16.4% higher carbonation depth than the control concrete after 360 days.

3.7 Correlation between carbonation depth, Sorptivity, and permeability.

The accumulation of CO2 in concrete is dependent on the porosity and permeability of the concrete. Therefore, a correlation between carbonation depth and sorptivity, and permeability have been studied using the linear regression method. The correlation between carbonation depth and sorptivity values has been presented in Fig. 25(a). It can be observed that the correlation has an R-square value of 0.6787. The correlation between carbonation depth and coefficient of permeability is presented in Fig. 25(b). The coefficient of permeability is better correlated than the coefficient of sorptivity with 360 days of carbonation depth. Table 4 presents the regression equations along with their standard errors. The multivariable equation was generated by regression of Sorptivity and permeability both parameters as input and carbonation depth as the output parameter. Figure 26 presents the comparison between the predicted values of carbonation depth by the multivariable equation and the experimental carbonation depth. The multivariable equation is more precise than the single variable equations with a comparatively higher R-square value.

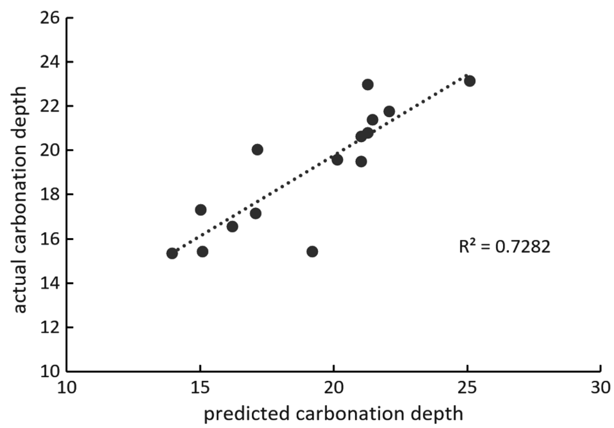

Fig. 26 — experimented carbonation depth vs predicted values of carbonation depth from the values of sorptivity and permeability.

4 Conclusion

Based on the experimental study following conclusion has been drawn

- The incorporation of RHA in concrete improves the resistance of concrete against rebar corrosion. However, the application of RHA should be carefully implemented for the best possible performance. The optimum percentage of RHA has been found to be 5 to 10% in the experimental investigations. The experimental study had been carried out on concrete samples of 0.38, 0.46, and 0.54 w/b ratios. In 0.38 w/b ratio samples, 5% RHA has been proven to be the optimum. In the other samples, 10% RHA yields the best results.

- The HCP values show that the de-passivation starts after 60 to 90 days for the control BAC. However, at optimum RHA% depassivation starts after 90 to 120 days of exposure. Which is a significant improvement over control concrete. The samples with optimum RHA% show 3.5% to 15.99% higher HCP values than the corresponding control BAC after 360 days of exposure. Higher values of HCP values indicate a lower probability of corrosion.
- Similar to the HCP values the best resistivity values were also found with 5% RHA at lower w/b ratios and with 10% RHA for higher w/b ratios. After 360 days of chloride exposure concrete samples with optimum RHA percentage the samples with optimum RHA% show 4 to 6 kOhm higher resistivity values than the control concrete of similar w/b ratios.
- The 5% to 10% RHA was also proved to be optimum in the carbonation depth test of the concrete samples. The average carbonation depth of the optimum samples was observed to be 3 to 6 mm lower than the control BAC after 360 days of exposure time.
- Values of HCP and resistivity have a good correlation with the actual mass loss of reinforcement steel bars. The R-square value of the single variable regression of HCP and mass loss was observed to be 0.638. The R-square value of the regression of the resistivity and actual mass loss was found to be 0.595. The R-squared value of the multivariable regression of the three variables was observed to be 0.646.
- The coefficient of permeability and sorptivity both parameters possessa good correlation with the carbonation depth of the concrete samples. However, the correlation between permeability and carbonation depth is marginally better than that of sorptivity and carbonation depth. Both parameters can be used together for the prediction of carbonation depth.

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