Evaluation of bagasse ash as corrosion resisting admixture for carbon steel in concrete

K. Ganesan and K. Rajagopal
Alagappa Chettiar College of Engineering and Technology, Karaikudi, India, and

K. Thangavel
Central Electro Chemical Research Institute, Karaikudi, India

Abstract

Purpose – Utilization of industrial and agricultural waste products as cement replacement materials in concrete technology has been an interesting subject of research for economical, environmental, and technical reasons. Portland cement incorporating these cement replacement materials improves corrosion resistance of carbon steel. Sugar cane bagasse is considered as waste in sugar mills and dumped in open space or used as fuel for boilers. The main purpose of the study is to investigate corrosion performance of reinforcing carbon steel in bagasse ash (BA) blended cement concrete and compare it with control concrete.

Design/methodology/approach – BA is prepared by burning boiler-fired ash at a controlled temperature of 650°C for 1 h and cooled. The ash is then ground to a fineness of 46 μm as Pozzolanic material and blended in concrete in various cement replacement levels. The corrosion behaviour of carbon steel in BA blended concretes exposed to alternate dry-wet cycles in 3.0 percent NaCl solution for 18 months was studied using gravimetric weight loss, linear polarization, and electrochemical impedance measurement techniques. The resistance to chloride ion penetration of BA blended concretes after 28 and 90 days and compressive strength of BA blended concrete cubes after 7, 14, 28, and 90 days curing also was evaluated.

Findings – The experimental results indicated that the corrosion rate of reinforcing steel and chloride penetration were significantly reduced, and compressive strength was increased, with the incorporation of BA up to 20 percent replacement in concrete. It was observed also that a relatively good correlation between linear polarization and impedance measurements with respect to corrosion current values on the reinforcing steel within BA blended concretes.

Originality/value – BA may be considered as a better substitute than other mineral admixtures for durable concrete structures. The study fulfilled the objective of the investigation and contributes to research on corrosion protection of carbon steel in concrete.

Keywords Ashes, Concretes, Corrosion, Compressive strength

Paper type Research paper

Introduction

A major problem concerning the durability of reinforced concrete structures is corrosion of the steel reinforcement. Transport of species such as chloride, sulphate, and carbon dioxide through the interconnected pore spaces of the concrete has been identified as a major material characteristic and in many cases, a rate-controlling parameter for the corrosion reaction (RILEM TC, 1999). It is well documented that Portland cement concrete incorporating Pozzolanic materials develops excellent mechanical properties and long-term durability by reducing permeability and the diffusion of moisture and aggressive species to the steel concrete interface (Cook, 1986; Saricimen *et al.*, 1995). In addition, the use of these Pozzolanic materials influence the corrosion of embedded steel reinforcement through the pore fluid which contains corrosion inducing elements such as chloride ion concentration and alkalinity (OH^- concentration) (Manget and Molly, 1991). The effect of fly ash addition on the corrosion resisting characteristics of concrete has been studied and it was reported that half-cell potentials up to 2,000 days (when 20 percent fly ash was used) did not pose any threat to the protection of reinforcing bars in concrete (Maslehuddin *et al.*, 1987). Ping *et al.* (2000) studied the performance of reinforcing steel in concrete containing silica fume and blast furnace slag by the half-cell potential, linear polarization and the impedance measurement techniques found that there was no significant corrosion in the silica fume and slag concrete and the poorest performance was observed in the control concrete. Zhang and Malhotra (1996) studied the chloride permeability of high-performance concrete incorporating rice husk ash (RHA) at different replacement levels of ordinary Portland cement (OPC) using the ASTM Standard C1202 method and found that RHA concrete with 10 percent replacement of cement had excellent corrosion performance. The above results, in general, show that the mineral admixtures improve the corrosion resistance of steel in concrete. Apart from these materials, a number of other waste materials have been used as blending components (Hasan *et al.*, 1999; Demirbas and Asia, 1998). Bagasse ash (BA) is one of such wastes that can be used as a blending material. Singh *et al.* (2000) studied the Pozzolanic properties of BA blended Portland cement and observed that in the presence of 10 percent of BA, the compressive strength values were higher than OPC and the reduction in permeability of mortars in its presence was established. The Pozzolanic properties of BA also have been studied and it was reported that BA can be reused as a Pozzolanic material in concrete (Hernandez *et al.*, 1998, 2000, 2001; Paya *et al.*, 2002).

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Earlier reports illustrated the studies carried out only on the physical and mechanical properties of BA blended mortars and concretes. The corrosion resistance property of BA blended concretes has not yet been studied. India, as one of the largest producers of sugar cane in the world, processes 300 million tons per year and bagasse is available as waste from the sugar mills. Hence, the objectives of the present investigation were to study the corrosion resistance properties of BA blended concrete and to identify the critical optimal level for replacement of cement.

Experimental

Materials

- *Cement*. OPC of 43 grade, conforming to Indian Standard IS8112 was used. The physical and chemical analyses of the cement used are given in Table I.
- *BA*. Boiler burnt BA was collected from Perry Sugar Mill, Aranthangi, which is in the Pudukottai District in Tamilnadu, India. It was further burnt at 650°C for 1 h under controlled conditions to remove the excess carbon and pulverized into fine powder as a Pozzolanic material. The physical and chemical analyses of BA are also given in Table I.
- *Aggregates*. Graded river sand passed through 1.18 mm sieve with fineness modules of 2.85 and specific gravity of 2.55 were used as fine aggregates. The coarse aggregate was locally available crushed granite aggregate, passing through 12.5 mm and retained on 4.75 mm sieve with fineness modules of 6.26 and specific gravity of 2.7 (conforming to IS 383-1970)
- *Steel reinforcement*. Carbon steel of Fe 415 grade conforming to IS 1786-1979 and 12 mm in diameter was used.

Preparation of test specimens

The BA was added in concrete by replacing an equal amount of OPC by percentage mass (5, 10, 15, 20, 25, and 30 weight percent). Initially, the BA was blended thoroughly with OPC in dry conditions, subsequently with sand and then coarse aggregate. Finally, water was added and evenly mixed to obtain a uniform composition. Six different proportions of BA concrete mixes and a control mix were prepared with a constant water to binder ratio of 0.53 for a design mix of M_{25} (Mix 1: 1.5: 3.0 for target cube compressive strength of 25 MPa). These mixes were designated as C for control and B1 to B6 for 5-30 percent replacement of BA blended concretes. The concrete was mixed in a laboratory mixer. The properties of the fresh concrete, including the slump and compaction factor, were determined. The slump of the concrete ranged from 50 to 110 mm and the compaction factor = 0.825 to 0.896.

BA-blended concrete cube specimens of size 100 × 100 × 100 mm embedded with one 12 mm diameter reinforcing steel bar at one of the corners with 20 mm cover were cast for electrochemical testing, as shown in Figure 1. The embedded area of the reinforcing steel bars was 28 cm^2.

Separate sets of BA-blended concrete cube specimens of size 100 × 100 × 100 mm with embedded 12 mm diameter and 50 mm long steel specimen coupons with 20 mm cover were cast for weight loss evaluation.

Plain BA blended concrete cubes of size 100 × 100 × 100 mm were fabricated for compressive strength tests and cylindrical specimens of size 100 mm diameter and 50 mm in thickness were cast for the chloride permeability tests. Triplicate specimens were cast for each mix and each test. The samples were demoulded after 24 h and were subjected to water curing.

Methodology

Compressive strength test

The compressive strength of concrete cubes of size 100 × 100 × 100 mm after 7, 14, 28, and 90 days moist curing were determined according to IS10261-1982.

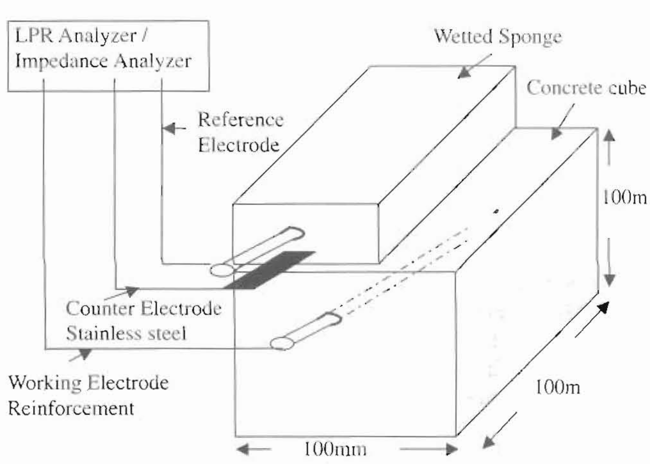
Resistance to chloride ion penetration test

The resistance of the concrete to the penetration of the chloride ions, measured in terms of total charge passed through the concrete cylindrical specimens of size 100 mm diameter and 50 mm thickness after 28 and 90 days moist curing were determined according to ASTM C 1202.

Table I Physical properties and chemical analysis of OPC and BA

Details	PPC	BA
Physical properties		
Specific gravity	3.1	1.85
Fineness passing 45 μm sieve (percent)	80	99
Specific surface area Blains (m^2/Kg)	326	843
Specific surface area BET (m^2/g)	–	10.50
Mean grain size (μm)	19.8	4.60
Chemical analysis		
Silicon dioxide (SiO_2)	20.25	64.15
Aluminium oxide (Al_2O_3)	5.04	9.5
Ferric oxide (FeO)	3.16	5.52
Calcium oxide (CaO)	63.61	8.14
Magnesium oxide (MgO)	4.56	2.85
Sodium oxide (Na_2O)	0.08	0.92
Potassium oxide (K_2O)	0.51	1.35
Loss on ignition (LOI)	3.12	4.90

Figure 1 Electrochemical measurement set up



Gravimetric weight loss method

BA blended concretes and control concrete specimens embedded with pre-weighed steel coupons were broken open and rebar coupons were cleaned as per ASTM G1-90 after the end of an 18-month dry-wet exposure cycle in 3.0 percent NaCl solution. The final weight of the steel coupons was measured. From the weight loss, the corrosion rate (CR) of embedded steel was calculated using the following equation:

$$\text{Corrosion rate (mmpy)} = \frac{87.6 \times \text{loss in weight (mg)}}{\text{Density (g/cm}^3) \times \text{area (cm}^2) \times \text{time (hours)}} \quad (1)$$

Electrochemical tests

The electrochemical experiments were conducted using Advanced Corrosion Monitoring (ACM) field instrument and related software package. This system includes a potentiostat/galvanostat and impedance analyzer with personal computer. A three electrode cell configuration, consisting of reinforcing steel bar embedded in concrete as working electrode, stainless steel plate of equal area as counter electrode, and saturated calomel electrode (SCE) as reference electrode was used. The counter electrode and the reference electrode were assembled in a wetted sponge of 100 × 50 × 30 mm in size. Linear polarization resistance (Rp) and electrochemical impedance measurements were carried out by placing the wetted sponge assembly on the surface of the concrete over the working electrode as shown in Figure 1.

Linear Rp test

Linear Rp measurements were carried out within the potential range of −20 mV to + 20 mV with respect to open circuit potential and the current response was measured at a scan rate of 0.166 mV/sec. IR compensation was applied during the measurements. The Rp of the reinforcing steel in BA blended concrete was obtained as the slope of the potential-current plot. In addition, the corrosion potential (Ecorr), corrosion current (Icorr) and CR were estimated from the polarization studies using the following relationships (Andrade and Gonzales, 1986; Manget and Molly, 1991):

$$\text{Corrosion current, (Icorr)} = \frac{B}{\text{Rp}} \ (\mu\text{A/cm}^2) \quad (2)$$

where B = Stern-Geary Constant (B = 26 mV SCE) and Rp in KΩ-cm^2.

$$\text{Corrosion rate (CR)} = \frac{301 \times 10^{-3}}{\text{Rp}} \ \text{(mmpy)} \quad (3)$$

Electrochemical impedance tests

Impedance measurements were carried out at open circuit potential with an a.c. amplitude of 15 mV. The impedance and phase angle were measured for the frequency range of 30 KHz-10 mHz as per ASTM G 106-89. The impedance data were displaced in the form of Nyquist plot and the charge transfer resistance (Rct) was obtained from the Nyquist plot. The Icorr and CR values were also estimated from Rct values using the following expressions.

$$\text{Corrosion current (Icorr)} = \frac{\text{B}}{\text{Rct}} \ (\mu\text{A/cm}^2) \quad (4)$$

$$\text{Corrosion rate (CR)} = \frac{301 \times 10^{-3}}{\text{Rct}} \ \text{(mmpy)} \quad (5)$$

For the quantitative assessment of corrosion inhibitive performance of reinforcing steel in BA blended concretes, the percentage reduction in CR of steel in BA concrete systems were estimated using following equations:

$$\text{Percentage reduction in CR} = \frac{1/\text{Rp} - 1/\text{Rp}_{(B)}}{1/\text{Rp}} \times 100 \quad (6)$$

$$\text{Percentage reduction in CR} = \frac{1/\text{Rct} - 1/\text{Rct}_{(B)}}{1/\text{Rct}} \times 100 \quad (7)$$

$$\text{Percentage reduction in CR} = \frac{\text{CR} - \text{CR}_{(B)}}{\text{CR}} \times 100 \quad (8)$$

where Rp and $\text{Rp}_{(B)}$ are the linear Rp values in the absence and presence of BA, Rct and Rct $_{(B)}$ are charge Rct values in the absence and presence of BA and CR and $\text{CR}_{(B)}$ are the CR values in the absence and presence of BA, respectively.

Results

Compressive strength test

The compressive strength of the "control" concrete and concrete with different percentages (0-30) of BA, tested after 7, 14, 28, and 90 days of curing are summarized in Table II. As anticipated, the compressive strength of control concrete and BA concretes increased with curing times.

Resistance to chloride ion penetration test

The relationship between the chloride ion penetration, measured in terms of the total charge passed (coulombs) and the curing periods (28 and 90 days), for control concrete and concrete incorporating BA are shown in Table II. The total charge passed values were reduced considerably in BA-blended concretes up to 30 percent CRL after 28 and 90 days of curing.

Gravimetric weight loss method

The CR values obtained from gravimetric weight loss method on the steel coupons embedded in the concrete cubes are shown in Table III. The CR measured by the gravimetric weight loss method clearly show that the BA blended concretes had higher corrosion resistance properties up to 25 percent CRL than did the "control" sample concrete. The percentage reduction in CR also is reported in Table III.

Linear Rp test

The Rp value and corresponding Ecorr, Icorr and CR measured for all specimens at the end of 18 months dry-wet cycles are presented in Table IV. The BA blended concretes up to 25 percent CRL had higher Rp values than the control concrete with consequently lower CR than control concrete at initial stage and final stage after 18 months. The percentage reduction in CR of the specimens calculated using Rp and $\text{Rp}_{(B)}$ values also are presented in Table IV.

Electrochemical impedance measurement test

The Rct value and corresponding Ecorr of reinforcing steel in BA blended concrete and control concrete were determined

Table II Compressive strength and resistance to chloride ion penetration of BA concretes

Specimen	BA replacement level (percent)	Compressive strength (M Pa) 7 days	14 days	28 days	90 days	Resistance to chloride penetration in coulombs 28 days	90 days
C	0	27.22	32.30	36.05	38.30	2,775	2,480
B1	5	31.11	34.60	41.30	44.00	2,046	1,605
B2	10	34.12	40.90	42.10	44.10	1,854	1,374
B3	15	34.09	39.90	41.21	43.00	1,302	874
B4	20	33.90	37.60	39.80	40.70	1,203	760
B5	25	32.57	33.10	33.60	36.70	1,050	681
B6	30	29.56	30.40	30.80	31.60	2,086	1,289

Table III Gravimetric method of corrosion rate values of BA blended concrete

Specimen	BA replacement level (percent)	Corrosion rate $\times 10^{-3}$ mmpy	Percentage reduction in CR $CR-CR_{(B)}/CR$
Control	0	21.63	
B1	5	15.42	28.71
B2	10	6.02	72.16
B3	15	8.12	62.45
B4	20	11.71	45.86
B5	25	16.24	24.91
B6	30	84.56	−290.91

Table IV Linear polarization resistance value and corrosion rates of BA concretes

Specimens	BA replace-ment level (percent)	Corrosion potential (mV SCE)	Rp $k\Omega - cm^2$	Icorr $\mu A/cm^2$	Corrosion rate $\times 10^3$ mmpy	percentage reduction in CR $(1/Rp) - (1/Rp_{(B)})/(1/Rp)$
Control	0	495	14.943	1.74	20.14	–
B1	5	361	33.147	0.784	9.08	54.92
B2	10	321	110.91	0.234	2.71	86.54
B3	15	359	54.09	0.481	5.56	72.39
B4	20	430	31.63	0.822	9.51	52.78
B5	25	441	27.43	0.948	10.97	45.53
B6	30	490	6.681	3.89 ×	45.05	−123.68

from using the impedance technique and the results are presented in Table V. An equivalent circuit for the experimental impedance spectra is shown in Figure 2. The results are presented in the Nyquist plots of real versus imaginary part of the impedance and Bode plots (by impedance versus log frequency and phase angle versus log frequency). The values of Rct were determined using the "best fit" approach. The BA blended concretes up to 25 percent CRL had higher Rct values than control concrete. The percentage reduction in CR values estimated using Rct and Rct (B) are also given in Table V.

Discussion

Compressive strength

The control concrete exhibited a compressive strength of 36.05 N/mm^2 and 38.3 N/mm^2 at 28 days and 90 days of curing. The compressive strength value was increased by 17 percent in 10 percent BA blended concrete after 28 days curing. The compressive strength values of BA blended concretes up to 20 percent CRL were higher than for the control concrete at 28 days and 90 days. The increase in compressive strength may have been due to the higher amount of reactive silica content of BA, which favoured the additional CSH gel formation to enhance the strength.

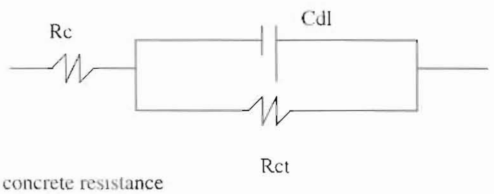
Resistance to chloride ion penetration

The performance of concrete against the chloride ion permeability of concrete was estimated in terms of total charge passed. For the "control" concrete, the total charge passed was 2,775 C at 28 days and 2,480 C at 90 days curing. The accumulated charge passed values for BA blended concrete varied in the range of 1,050-2,086 C for 28 days and 681-1605 C for 90 days, respectively. According to ASTM C 1202, concrete with a charge passed value between 1,000 and 2,000 C is considered to have a good resistance to the penetration of chloride ions. The results of accumulated charge passed values of BA blended concrete showed good resistance to the penetration of chloride ions. The BA concretes had 1.55-3.64 times higher resistance to chloride

Table V Impedance measurement values and corrosion rates of BA concretes

Specimens	BA replacement level (percent)	Corrosion potential (mV SCE)	Rct kohms − cm^2	Icorr $\mu A/cm^2$	Corrosion rate × 10^3 mmpy	Percentage reduction in CR (1/Rct)−Rct(B)/(1/Rct)
Control	0	448	12.31	2.119	24.45	–
B1	5	353	19.56	1.334	15.38	37.10
B2	10	341	101.50	0.257	2.96	87.89
B3	15	359	34.89	0.745	8.63	67.70
B4	20	395	28.26	0.920	10.65	56.44
B5	25	449	16.50	1.575	18.24	25.39
B6	30	488	3.994	6.509	75.36	− 208.22

Figure 2 Equivalent circuit model for impedance results



where Rc = concrete resistance
Cdl = double layer capacitance
Rct = Charge transfer resistance

ion penetration than did the control concrete at 90 days. This higher resistance to chloride ion penetration of BA concretes was due to the filler effect of the BA particles.

Gravimetric weight loss results

For control concrete, the CR of embedded steel was 21.63×10^{-3} mmpy and the CR of steel in BA concretes ranged from 6.02 × to 84.56×10^{-3} mmpy. The values of CR for all the reinforcing bars in BA blended concretes up to 25 percent replacement were less than 20×10^{-3} mmpy up to 18-months dry-wet cycles. Steel embedded in BA-blended concrete with 10 percent CRL showed a 3.6 times decrease in CR compared to the "control" concrete. The percentage reduction in CR data reported for BA blended concretes also revealed a maximum value of 72.16 at 10 percent CRL and even at 25 percent CRL the percentage reduction in CR was found to be 24.91. These results showed that the introduction of Pozzolanic material (BA) in blended concrete improved the resistance of the material to chloride-induced corrosion of steel.

Linear Rp

The "control" concrete showed a CR value of 20.14×10^{-3} mmpy and the range of CR values of BA concrete after 18 months dry-wet cycle were 2.71 × to 45.05×10^{-3} mmpy. The lowest CR was found to be 2.71×10^{-3} mmpy for BA concrete with 10 percent CRL and the CR value was reduced by a factor of 7.5 times. The percentage reduction in CR reported also revealed a maximum value of 86.54 at 10 percent CRL. Even at 25 percent CRL, the percentage reduction in CR was 45.53. These data also clearly showed that the finer BA particles considerably refined the pore structure and reduced the CR of embedded steel.

Impedance measurements

The "control" concrete showed a CR value of 24.45×10^{-3} mmpy and the range of CR values of BA concrete after 18 months dry-wet cycles were 2.96×10^{-3} to 75.36×10^{-3} mmpy. The lowest CR was 2.96×10^{-3} mmpy for BA concrete with 10 percent CRL. A maximum reduction of 8 times in CR value was found in concrete with 10 percent CRL. The percentage reduction in CR reported also revealed that a maximum value of 87.89 at 10 percent CRL. At 25 percent CRL, the percentage reduction in CR value was found to be 25.39. These data again suggest that the formation of additional calcium silicate hydrate (C-S-H gel) during the hydration of BA concrete may be responsible for transformation of large permeable pores to small impermeable pores and improvement in corrosion resistance of steel in BA concretes.

The results obtained from impedance studies concrete containing BA at 0, 10, and 25 percent replacement levels are presented in Bode plot and Nyquist plot formats, as shown in the Figure 3(a) and (b), respectively. The Nyquist diagrams showed typical semicircles, from which associated Rct values were calculated. From the Nyquist plot (Figure 3(b)), it was estimated that the concrete with 10 percent BA had the largest semicircular arc (maximum Rct value), followed by concrete with 25 percent BA, and the "control" concrete had the smallest semicircle, representing minimum Rct value. The Bode diagram also shows the same higher Rct + Rc values for 10 percent BA concrete.

Comparison of results of electrochemical techniques

Half-cell potentials obtained from the linear polarization and impedance measurement techniques were in close agreement. More negative half-cell potential readings were associated with higher Icorrs, as determined by both the linear polarization and impedance measurement techniques. The half-cell potential vs Icorr plots for linear polarization and impedance techniques are presented in Figure 4(a) and (b), respectively. A linear trend for the half-cell potential and Icorr relation was obtained (correlation coefficient, $R = 0.965$ for linear polarization and $R = 0.954$ for the impedance tests). The linear relationship between Ecorr and Icorr exists theoretically in chloride-induced corrosion (Ping *et al.*, 2000). A comparison plot of Icorr values obtained by the linear polarization and impedance measurement techniques is presented in Figure 5. A solid reference line was applied to indicate a linear trend between the measurements. It appeared that both techniques were in a relatively good agreement (correlation coefficient, $R = 0.93$) with respect to Icorr values when reinforcing is under active corrosion.

However, for all of these specimens, the CRs measured by weight loss methods on the rebar coupon were higher than were those estimated on the basis of the Icorr measured by the LPR and impedance methods. Nevertheless, CRs measured using LPR method, impedance method and weight loss method gave the same trends in the corrosion performance of reinforcing steel in BA concretes.