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Evaluation of bagasse ash as supplementary cementitious material

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Abstract

The utilization of waste materials in concrete manufacture provides a satisfactory solution to some of the environmental concerns and problems associated with waste management. Agro wastes such as rice husk ash, wheat straw ash, hazel nutshell and sugarcane bagasse ash are used as pozzolanic materials for the development of blended cements. Few studies have been reported on the use of bagasse ash (BA) as partial cement replacement material in respect of cement mortars. In this study, the effects of BA content as partial replacement of cement on physical and mechanical properties of hardened concrete are reported. The properties of concrete investigated include compressive strength, splitting tensile strength, water absorption, permeability characteristics, chloride diffusion and resistance to chloride ion penetration. The test results indicate that BA is an effective mineral admixture, with 20% as optimal replacement ratio of cement.

Keywords: Bagasse ash; Blended cement; Concrete; Compressive strength; Transport properties

1. Introduction

Ordinary Portland cement is recognized as the major construction material throughout the world [1]. Industrial wastes, such as blast furnace slag, fly ash and silica fume are being used as supplementary cement replacement materials. In addition to these, agricultural wastes such as rice husk ash, wheat straw ash, and sugarcane bagasse ash are also being used as pozzolanic materials and hazel nutshell used as cement replacement material [2–11]. When pozzolanic materials are added to cement, the silica (SiO_2) present in these materials reacts with free lime released during the hydration of cement and forms additional calcium silicate hydrate (CSH) as new hydration products [12], which improve the mechanical properties of concrete formulation. The ash produced by controlled burning of agro waste materials below 700 °C incinerating temperature for one hour transforms the silica content of the ash into amorphous phase [6,13] and the reactivity of amorphous silica is directly proportional to the specific surface area of ash [14,15]. The ash so produced is pulverized or ground to required fineness and mixed with cement to produce blended cement. Thus the agricultural ash properties depend on burning time, temperature, cooling time and grinding conditions [2,5,6,8].

India being one of the largest producers of sugarcane in the world, produces 300 million tons per year [16] and large quantity of sugarcane bagasse is available from sugar mills. Sugarcane bagasse is partly used as fuel at the sugar mill. Only a few studies have been reported on the use of bagasse ash (BA) as pozzolanic material in respect of cement paste [17–22]. The objective of the present investigation is to evaluate BA as supplementary cementitious material with reference to mechanical properties and permeability properties of hardened concretes and identify the optimal level of replacement. Towards this end, experiments were carried out in two phases as per standard test procedures. In the first phase, the chemical composition, physical properties, and characterization of BA were carried out. This included evaluation of water consistency, initial setting time, final setting time and compressive strength of BA blended cements. In the second phase, studies on concrete

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specimens were conducted. This included tests on compressive strength, splitting tensile strength, water absorption, and coefficient of water absorption, sorptivity, resistance to chloride ion penetration, and migration diffusion coefficient. All the experiments were carried out in triplicate and mean value reported.

2. Experimental program

2.1. Materials used

Ordinary Portland cement (OPC) conforming to Indian standard code IS 8112-1995 was used. Graded river sand passing through 1.18 mm sieve with fineness modulus of 2.85 and specific gravity of 2.55 was used as fine aggregate. The coarse aggregate was locally available crushed granite aggregate, passing through 12.5 mm sieve and retained on 4.75 mm sieve with fineness modulus of 6.26 and specific gravity of 2.7 (Conforming to IS 383-1970).

Mill-fired BA was collected from E.I.D. Parry Sugar mill, Aranthangi in TamilNadu, India. The uncontrolled boiler fired ash was black in colour due to 11.2% carbon content. The mill fired BA was further burnt under controlled temperature at 650 °C for one hour. This burning process brought down the carbon content to 4.9%. After cooling, the ash was ground to 5.4 μm mean grain size before it was used as a cement replacement material.

2.2. Physical and chemical analysis of OPC and BA

Particle size distribution of OPC and BA was determined using HORIBA LA-910 particle size analyzer. Mineralogical analysis of BA was carried out by X ray diffraction analysis. Specific surface area of OPC and BA were obtained using Blain's air permeability apparatus as per IS 4031 (Part 2)-1995. Physical properties such as specific gravity, bulk density, and fineness of OPC and BA were determined as per IS 4031 (Parts)-1995 and IS 1727-1995.

Chemical analysis for oxide composition of OPC and BA was determined as per IS 4032-1985 and IS 1727-1995.

2.3. Blended cements

BA blended cements were prepared by replacing OPC with different amount of BA (5, 10, 15, 20, 25 and 30 wt%) in dry condition. The mixtures were thoroughly homogenized and kept in polythene bottles before use.

2.4. Mix proportions and casting of concrete specimens

Seven different proportions of concrete mixes (BA ranging from 5% to 30% by weight of cement) including the control mix were prepared with a water binder W/(C + BA) ratio of 0.53 for a design cube compressive strength of 25 N/mm^2. These mixes were designated as B0 for control and B1–B6 for BA concretes. The mix proportions are summarized in Table 1.

The concrete was mixed in a laboratory drum mixer for a total of five minutes. For mixes B0 through B6, twelve 100 mm × 100 mm × 100 mm cubes were cast from each mix for compressive strength testing. Three 150 mm × 300 mm cylinders were also cast from each mix for determining the splitting tensile strength. Thirty, 100 mm diameter × 50 mm thick cylindrical specimens were cast from each mix for water and chloride penetration tests. After casting, all specimens were left covered in the casting room for 24 h. The specimens were then demoulded and transferred to moist curing room until the time of testing.

2.5. Consistency and setting time of blended cement

Water consistency of BA blended cements was determined in accordance with IS 4031 (Part 4)-1995. Then the pastes having normal consistency were used to determine the initial setting time and final setting time in accordance with IS 4031 (Part 5)-1995.

2.6. Compressive strength of blended cement

The compressive strength of BA blended cement mortar cubes (mix 1:3) was determined after 7 and 28 days moist curing as per IS 4031 (Part 6)-1995. Mortar mixes were designated as M0 for control and M1–M6 for BA blended mortars. The BA blended cement mortar mix proportions are presented in Table 2.

2.7. Compressive and splitting tensile strength of concrete

Compressive strength of BA blended cement concrete cubes was determined after 7, 14, 28 and 90 days moist curing as per IS 9013-1997. Splitting tensile strength test was conducted on BA blended concrete cylinders after 28 days of moist curing as per IS 5816-1999.

2.8. Water absorption

Percentage of water absorption is a measure of the pore volume or porosity in hardened concrete, which is occupied by water in saturated condition. Water absorption values of BA blended concrete specimens after 28 and 90 days of moist curing were measured as per ASTM C642. The difference between the saturated mass and oven dry mass expressed as a fractional percentage of oven dry mass gives the water absorption.

2.9. Coefficient of water absorption

Coefficient of water absorption is suggested as a measure of permeability of water [23]. This is measured by the rate of uptake of water by dry concrete in a period of one hour. Coefficient of water absorption values of BA

Table 1
Mix proportions of BA blended concretes

Mix designation	BA (%)	W/C or W/(C+BA)	Quantities (kg/m^3)					
			Water	Cement	BA	Sand	Aggregate	Slump in mm
Control, B0	0	0.53	203	383	0	575	1150	98
B1	5	0.53	203	364	19	575	1150	106
B2	10	0.53	203	345	38	575	1150	115
B3	15	0.53	203	326	57	575	1150	91
B4	20	0.53	203	306	77	575	1150	81
B5	25	0.53	203	287	96	575	1150	74
B6	30	0.53	203	268	115	575	1150	64

Where C is the cement; W is the water and BA is the bagasse ash.

Table 2
Compressive strength of BA blended cement mortars

Mix designation	BA (%)	(C + BA):sand	Compressive strength (N/mm^2)	
			7 days	28 days
M0 (Control)	0	(1 + 0):3	21.52[a]	28.31[a]
M1	5	(0.95 + 0.05):3	27.97	33.38
M2	10	(0.90 + 0.1):3	28.12	33.86
M3	15	(0.85 + 0.15):3	26.39	32.06
M4	20	(0.80 + 0.20):3	21.43[a]	27.86[a]
M5	25	(0.75 + 0.25):3	20.04	26.14
M6	30	(0.70 + 0.3):3	18.45	25.07

[a] Equivalent strength compared to control specimen.

blended concrete specimens after 28 and 90 days of moist curing were determined using the formula

$$K_a = \left(\frac{Q}{A}\right)^2 \times \frac{1}{t}$$

where K_a is the coefficient of water absorption; Q is the quantity of water absorbed by the oven dry specimen in time, t; $t = 3600$ s (1 h) and A is the total surface area of concrete specimen through which water penetrates.

2.10. Sorptivity

Sorptivity is a measure of the capillary forces exerted by the pore structure causing fluids to be drawn into the body of the material [24]. The sorptivity values of BA blended concrete specimens after 28 days and 90 days moist curing were calculated by the following formula, based on the method developed at the university of Toronto, Canada [25]

$$i = St^{1/2}$$

where i is the cumulative water absorption per unit area of inflow surface; S is the sorptivity and t is the time elapsed.

2.11. Chloride penetration

The resistance to chloride ion penetration in terms of total charge passed values through BA blended concrete specimens after 28 days and 90 days moist curing were measured as per ASTM C 1202. The positive reservoir of the cell was filled with 0.3 M NaOH solution, while the negative reservoir was filled with 3% NaCl solution as shown in Fig. 1. A DC potential of 60 V was applied across the specimen faces, and the current was recorded every 30 min intervals, covering a total period of 6 h. By knowing the current and time history, the total charge (coulombs) passed through the specimen was computed by the following formula, based on trapezoidal rule.

$$Q = (I_0 + 2I_{30} + 2I_{60} + \cdots + 2I_{300} + 2I_{330} + I_{360})$$

where Q is the charge passed (coulombs); I_0 is the current (amperes) immediately after voltage is applied; I_t is the current (amperes) at time after voltage is applied.

2.12. Chloride diffusion

In this test concrete specimen was fixed in between two compartments of a diffusion cell containing 0.3 M NaOH solution and 3%NaCl solution as shown in Fig. 1. A DC potential of 12 V was applied to the titanium electrodes placed in the solutions. The amount of Chloride ion migrating through the BA blended concrete specimens after 28 days and 90 days moist curing was monitored, typically by periodically removing small aquilots and determining the chloride concentration of these samples, until steady state was reached (120 h), Using the data, chloride electrical migration diffusion coefficient values were calculated using Nernst–Einstein equation [26].

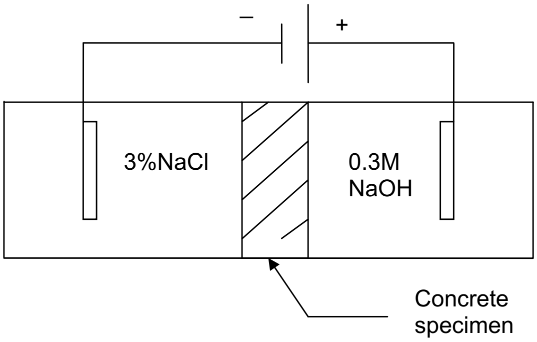

Fig. 1. Rapid chloride permeability test.

$$D = \frac{JRTL}{ZFC_0E}$$

where, D is the chloride migration diffusion coefficient; J is the flux of chloride ions (mol/cm^2 s); R is the gas constant (8.314 J/K mol); T is the absolute temperature (K); L is the thickness of the specimen (cm), Z is the valency of chloride ion ($Z = 1$), F is the Faraday's constant (9.648×10^{-4} J/Vmol); C_0 is the initial chloride ion concentration (mol/l); and E is the potential applied ($V = 12$ DC volts).

3. Results and discussion

3.1. Physical and chemical analysis of OPC and BA

The particle size distribution curves of OPC and BA are shown in Fig. 2. It can be seen that the particles of BA are nearly four times finer than those of OPC and the finer particles of BA are more uniform in their distribution. Mineralogical analysis of BA carried out by X-ray diffraction is shown in Fig. 3. The material consists essentially of an amorphous silica structure with a wide scattering peak (hump) centered at about 22° 2θ, Cu Kα radiation. Small quantities of crystal-phases as quartz and crystobalite are also present.

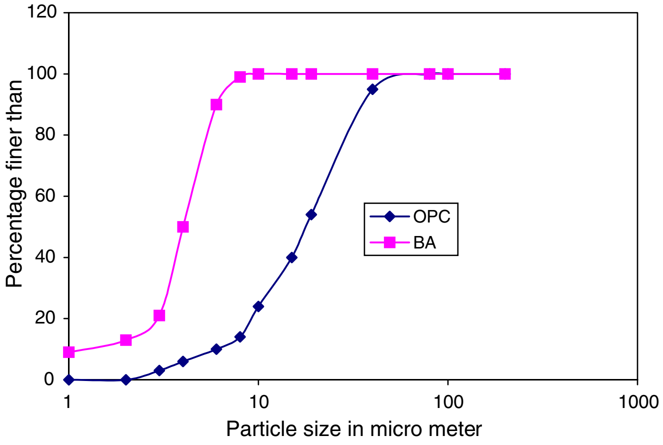

Fig. 2. Particle size distribution curves of OPC and BA.

The physical properties of OPC and BA are compared in Table 3. The specific surface area of BA is found to be three times higher than OPC. The density, specific gravity and mean grain size of BA are found to be less than those of OPC.

Chemical composition data for OPC and BA are compared in Table 4. The chemical analysis data indicate that BA has three times higher silica content than OPC. The BA also contains considerable amount of Al_2O_3, Fe_2O_3, and CaO.

3.2. Consistency and setting time of blended cement

The percentage of cement replacement level (CRL) versus consistency graph (Fig. 4) indicates that the water required for normal consistency increased with an increase in CRL. For example, the consistency measured for 0% and 20% CRL was found to be 0.32 and 0.49, respectively. As ashes are hygroscopic in nature and the specific surface area of BA is three times higher than cement it needs more water for proper consistency.

The percentage of CRL versus initial and final setting time chart (Fig. 5) shows that increasing the BA level considerably increases the initial and final setting time. The initial setting time measured for 0% and 20% CRL is found to be 79 min and 184 min, respectively. The final setting time measured for 0% and 20% CRL is found to be 300 min and 402 min, respectively. However all the values are well within the permissible limits as per IS 8112-1995.

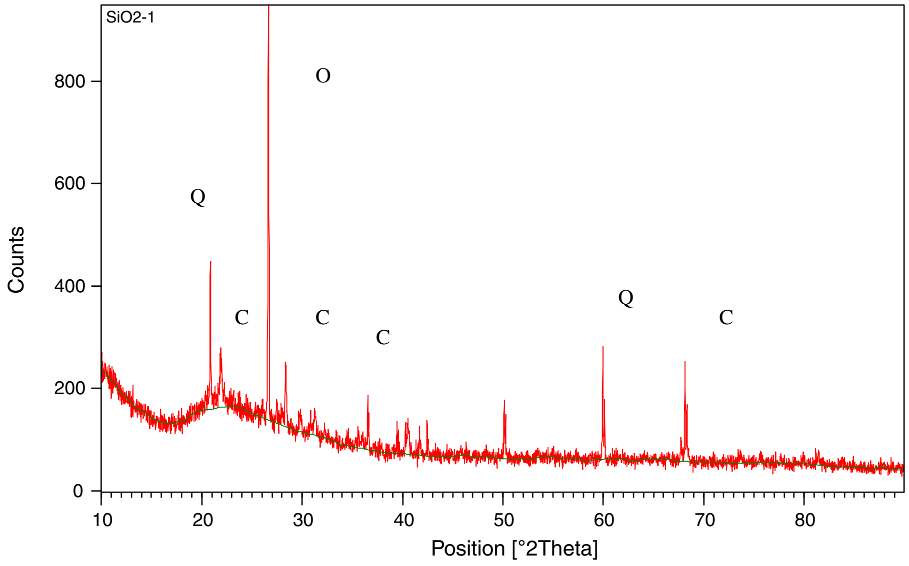

Fig. 3. X-ray diffraction analysis of BA.

Table 3
Physical properties of OPC and BA

Materials	Bulk density (g/cm^3)		Specific gravity	Fineness passing 45 μm sieve	Specific surface (Blain's) (m^2/kg)	Mean grain size (μm)
	Compacted	Loose				
OPC	1.56	1.16	3.1	85	326	22.50
BA	0.59	0.41	1.85	99	943	5.40

Table 4
Chemical composition of OPC and BA (%)

Materials	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	Loss on ignition
OPC	19.25	5.04	3.16	63.61	4.56	0.08	0.51	3.12
BA	64.15	9.05	5.52	8.14	2.85	0.92	1.35	4.90

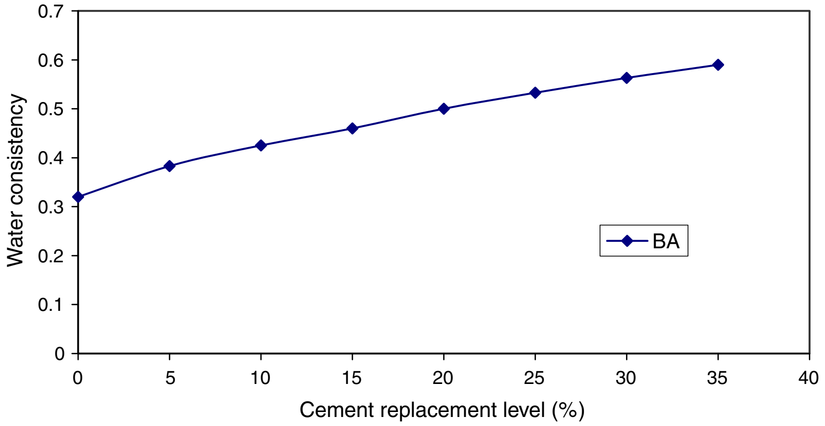

Fig. 4. Water consistency of BA blended cements.

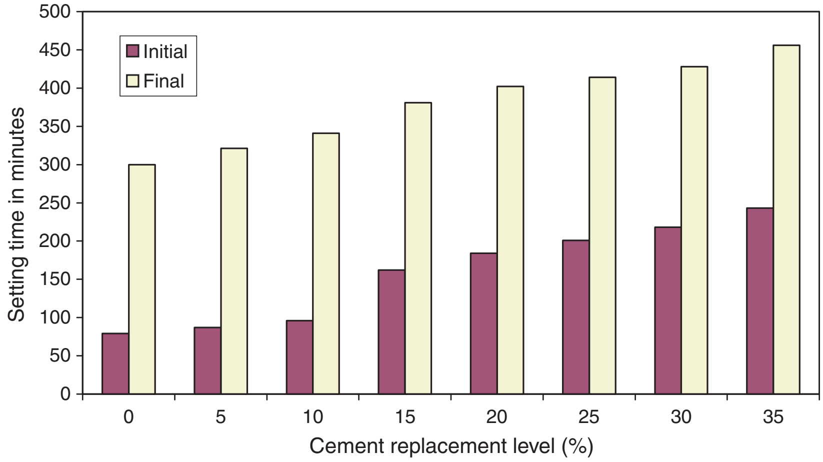

Fig. 5. Initial and final setting times of BA blended cements.

3.3. Compressive strength of blended cement

The compressive strength values of BA blended cement mortars are shown in Table 2. Comparison of the data for 7 and 28 days of curing time shows that the compressive strength increases with BA up to 10% and then at 20% BA the compressive strength of mortar attains the equivalent value as observed for control mortar. The increase in strength may be due partially to the pozzolanic reaction as reported by many researchers [17–22] and partially to high specific surface area of BA leading to number of nucleation sites for additional hydration products [18]. At 25 and 30% BA, the strength decreases to a lesser value when compared to that of control specimens. Thus 20% replacement of BA to OPC is considered as optimal limit.

3.4. Compressive strength of concrete

The compressive strength of BA blended concretes specimens are shown in Fig. 6. Comparison of the compressive strength data for 7, 14, 28 and 90 days of curing times shows that the compressive strength increases with BA up to 10% and then at 20% BA, the compressive strength of concrete attains equivalent values as that of control concrete specimens.

It is interesting to note that 7 days compressive strength value of 20% BA concrete is equivalent to 14 days compressive strength value of control specimen and 14 days compressive strength value of 20% BA concrete is equivalent to 28 days compressive strength value of control specimen. It is further observed that 28 days compressive strength value of 20% BA concrete is equivalent to 90 days compressive strength value of control specimen.

The relative increase in compressive strength of 20% of BA blended concretes compared to control concrete for all ages of curing is shown in Fig. 7. It can be seen that relative increase in compressive strength attains the maximum value (24.5%) at 7 days curing. At 14, 28 and 90 days, the relative increase in strength decreases. This confirms the fact that concrete with BA up to 20% develops early compressive strength as compared to control concrete specimens. The reasons for early compressive strength development of BA concretes and increase in compressive strength up to 20% cement replacement of BA may be due to silica content, fineness, amorphous phase, specific surface area, degree of reactivity of BA and pozzolanic reaction between calcium hydroxide and reactive silica in BA in the alkaline environment as reported by previous works [17–22]. At 25% and 30% of BA, the strength decreases to lesser value when compared

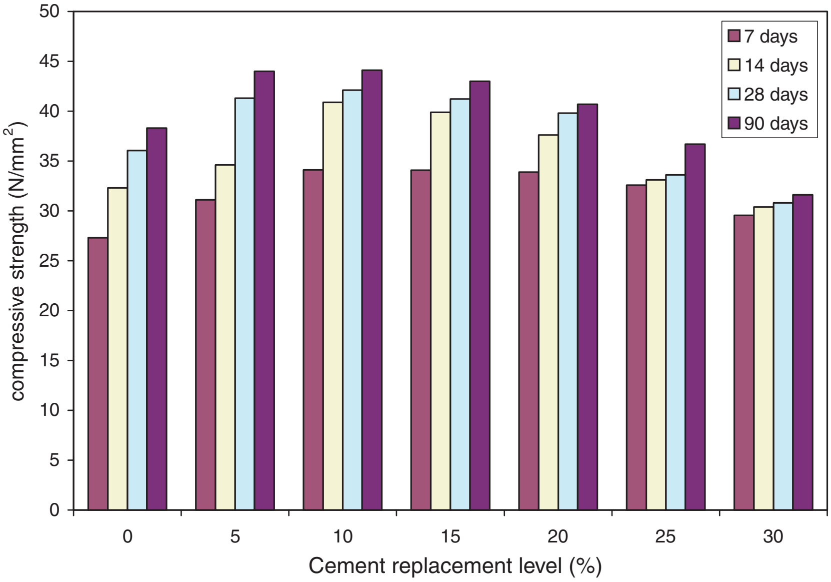

Fig. 6. Compressive strength of BA blended concretes.

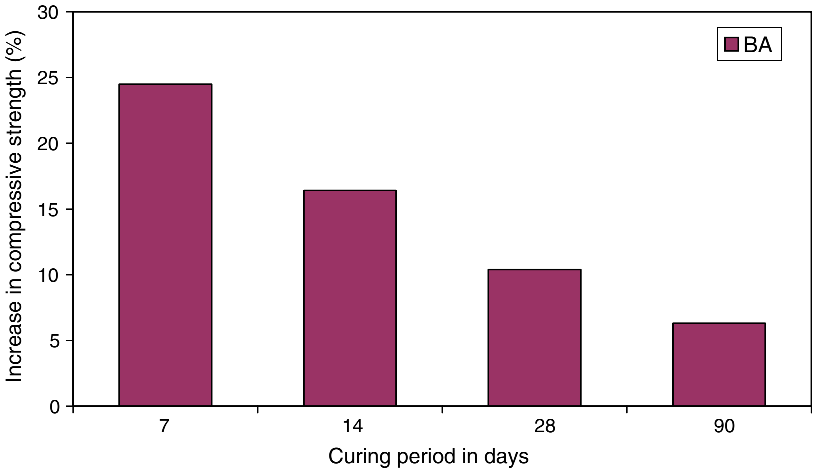

Fig. 7. Relative increase in compressive strength of 20% BA blended concretes.

to that of control specimens. Therefore 20% BA seems to be the optimal limit.

3.5. Splitting tensile strength

The splitting tensile strength values of BA blended concretes after 28 days of curing are shown in Fig. 8. It can be clearly seen that up to 20% of BA, the splitting tensile strength values increase and than at 25% and 30% of BA, the value decreases. Obviously from tensile strength point of view also, 20% of BA is the optimal limit.

3.6. Water absorption

Water permeability property as indicated by saturated water absorption values of BA blended concrete specimens after 28 and 90 days curing are given in Table 5. It can be seen that at 28 days curing the percentage of water absorption increases with BA content. This is due to the fact that BA is finer than OPC and also it is hygroscopic in nature. The percentage of water absorption values reduced considerably (50%) after 90 days curing. This is due to gradual closing of pores. Obviously with prolonged curing, addition of BA leads to reduction of permeable voids.

3.7. Coefficient of water absorption

From the coefficient of water absorption values of BA blended concrete specimens presented in Table 5, it can be seen that at 28 days curing, coefficient of water absorption values progressively decrease with increase of BA content and only at 30% BA there is significant increase in coefficient of water absorption value. At 90 days curing the values are correspondingly lower indicating that prolonged curing up to 90 days can turnout to be beneficial in this respect. It is also observed that at 20% BA content, concrete specimens show about 40% reduction in coefficient of water absorption value.

3.8. Sorptivity

The sorptivity values calculated for BA blended concrete specimens after 28 days and 90 days curing are also presented in Table 5. It can be seen that at 28 days curing, sorptivity progressively decreases with increase of BA content and only at 30% BA there is significant increase in sorptivity value. At 90 days curing, the values are correspondingly lower indicating that prolonged curing up to 90 days can turnout to be beneficial in this respect. It is also observed from the sorptivity data that 20% BA concrete specimen indicate 19% reduction at 28 days and 48% reduction at 90 days.

3.9. Chloride penetration

The Rapid chloride permeability test results for BA blended concrete specimens are shown in Fig. 9. It can be seen that the total (Coulombs) charge passing through

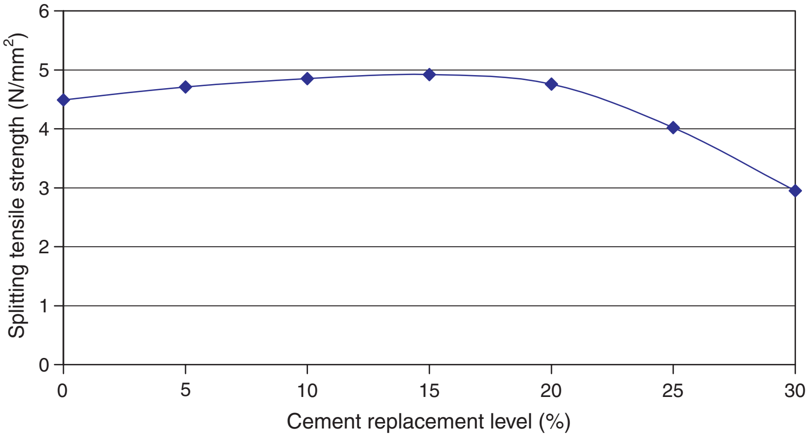

Fig. 8. Splitting tensile strength of BA blended concretes at 28 days curing.

Table 5
Permeability related properties of BA blended concretes

Mix designation	BA (%)	Saturated water absorption (%)		Coefficient of water absorption $\times 10^{-10}$ (m^2/s)		Sorptivity $\times 10^{-6}$ (m/s$^{1/2}$)	
		28 days	90 days	28 days	90 days	28 days	90 days
Control, B0	0	4.71	3.76	1.62	0.849	11.05	9.76
B1	5	4.78	3.01	1.27	0.701	8.96	6.85
B2	10	4.86	2.44	1.16	0.674	8.11	3.45
B3	15	4.90	2.21	0.91	0.563	7.47	3.05
B4	20	5.16	2.60	0.97	0.604	9.00	5.06
B5	25	5.56	2.72	1.00	0.632	10.04	5.76
B6	30	6.08	3.90	1.71	0.923	11.01	7.83

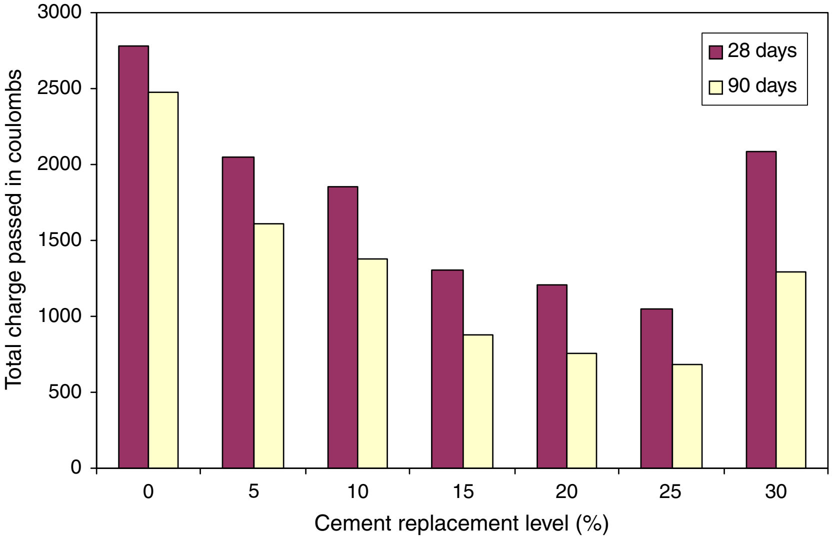

Fig. 9. Chloride permeability of BA blended concretes.

BA blended concrete specimens continuously decreases with increase in BA content up to 25% of BA. At 30% of BA, there is an increase, however the value is quite less compared to that of control. This observation is true for both 28days and 90 days cured specimens. This data indicate that chloride permeability is considerably reduced by partial replacement of OPC with BA. Particularly the total charge passed value for 20% BA blended concrete is considerably less (more than 50% reduction) both at 28 days and 90 days cured concretes.

3.10. Chloride diffusion

The chloride migration diffusion coefficients of BA blended concrete specimens are presented in Fig. 10. It can be seen that the diffusion coefficient of BA blended concrete specimens continuously decreases with increase in BA content up to 25% of BA. At 30% of BA, there is an increase, however the value is quite less compared to that of control. This observation is true for both 28 days and 90 days cured specimens. This data indicate that chloride diffusion is considerably reduced by partial replacement of OPC with BA. These results also indicate more than 50% reduction in diffusion coefficient value for 20% BA blended concrete when compared to control concrete.

Under introduction, it has been mentioned that only limited studies have been carried out on BA blended cements. According to Singh et al. [18] who had studied the hydration of BA–OPC blended cement, 10% addition of BA to OPC was considered as optimal limit based on compressive strength data of mortar. Their BA sample showed a loss on ignition value of 6.90% (due to unburnt carbon). Probably this value is on the higher side.

A study carried out by Hernandez et al. [17] showed that sugarcane bagasse ash collected from the mills did not act like pozzolana, mainly due to the presence of unburnt carbon.

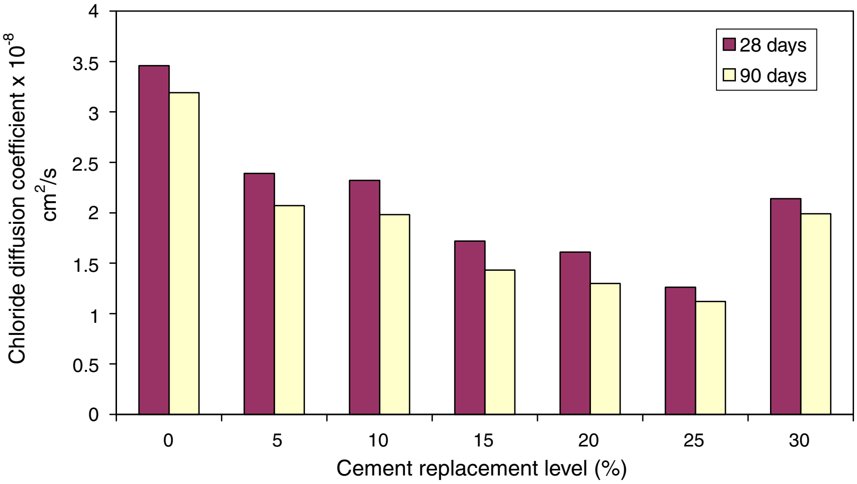

Fig. 10. Chloride diffusion of BA blended concretes.

Paya et al. [21] have reported that combustion yields ashes containing high amount of unburnt matter, silicon and aluminium oxides as main components. They have indicated that the bagasse ashes have to be chemically, physically and mineralogically characterized, in order to evaluate the possibility of their uses as a cement replacement material in concrete.

Cordeiro [22] had shown that mechanical grinding in a vibratory mill can significantly increase pozzolanic activity of the BA.

Thus it can be inferred that unburnt carbon content plays an important role in optimization. In the present investigation, the fineness of BA sample is three times higher than cement and BA contains silica mostly in amorphous form. Further the unburnt carbon content is only 4.9%.

The transport of chloride ions through BA blended concretes depends on the pore structure of the concrete while the electrical conduction depends on both pore structure characteristics and electrical conductivity of the pore solution [27–29]. The finer particles of ashes developed discontinuous and tortuous pore in concrete structure [30]. Moreover the micro and macro pores present in the concrete were completely filled up by finer particles. Cook [2] has reported that highly reactive pozzolana, such as rice husk ash are able to reduce the size of voids in hydrated cement pastes, thus making them almost impermeable even at early age (7–28 days). Singh et al. [18] confirmed the pore-refining capacity of BA when present in a Portland cement paste. Our studies also indicate that the impermeability properties are considerably improved due to pore refinement in BA blended concretes compared to control concrete.

To summarize, BA is finer than OPC and therefore it has a larger surface area to react. Owing to its fineness, presence of BA in OPC leads to an increase in water uptake. This increase obviously enhances the setting time (both initial and final). However the increase in setting time values are within the codal requirements. Once the final setting time is reached, hardening process begins. Since BA is richer in SiO_2 and Al_2O_3 contents, hardening process is accelerated. Presence of CaO in BA further helps in sustaining this hardening process. In fact, a part of SiO_2 in BA can primarily react with CaO in BA and supplement the hardening process taking place due to OPC. The amorphous silica structure and fine particle size are the principal reasons for the development of early strength. The development of splitting tensile strength is similar to that of compressive strength and is influenced by the same factors (replacement level, composition of BA and cement and fineness). The fineness of BA contributes to a finer pore structure and this fact is responsible for reduced chloride permeation and diffusion.

In general, the results obtained in this study clearly indicate that the addition of BA as cement replacement material provides additional improvements in strength and impermeability properties. Hence BA may be utilized as effective mineral admixture for designing durable concrete structures.

4. Conclusion

From the present investigation, the following conclusion can be drawn. Up to 20% of ordinary Portland cement can be optimally replaced with well-burnt bagasse ash without any adverse effect on the desirable properties of concrete. The specific advantages of such replacement are:

(i) Development of high early strength.
(ii) A reduction in water permeability and
(iii) appreciable resistance to chloride permeation and diffusion.

The above observations have a direct bearing on the durability of reinforced concrete structures.

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