




Mechanical and durability properties of bagasse ash-blended high-performance concrete

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Abstract

The use of supplementary cementitious materials has become an integral part of high-strength and high-performance concrete mix design, which may be natural by-products or industrial wastes. Some of the frequently used supplementary cementitious materials are fly ash, silica fume, ground granulated blast furnace slag, rice husk ash and bagasse ash (BA). BA (sugarcane industry waste product) is considered to be an active pozzolan because of its large surface area with significant amount of amorphous SiO_2 . The mix design for high-performance concrete is done as per the method proposed by P. C. Aitcin. This method is simple and follows the same approach as ACI 211-1 standard practice for selecting proportion of normal, heavy and mass concreting. Ordinary Portland cement was replaced at different levels of 0%, 5%, 10%, 15% and 20% by BA. This investigation presents results on the strength and durability properties of high-performance concrete with and without BA, which includes cube compressive strength, splitting tensile strength, flexural strength, saturated water absorption, sorptivity, porosity, impact test and alkalinity measurement. The test results indicate that the incorporation of BA up to 10% provides improved properties of hardened concrete.

Keywords Bagasse ash · High-performance concrete · Mechanical properties · Durability properties

1 Introduction

Major construction projects today around the world use ordinary Portland cement as a binder for manufacturing of mortar and concrete [1]. Production of cement emits carbon dioxide worldwide, which causes environmental issues such as dust pollution and thinning of ozone layer, which leads to global warming [2]. Utilization of supplementary cementitious materials as a partial replacement of cement mortar and concrete is the most effective way of reducing the environmental impact, which also minimizes energy, cost and waste emission [3, 4]. The wastes from various industries such as silica fume, fly ash and blast furnace slag were used as mineral admixtures. Bagasse ash, rice husk ash and wheat straw ash were also being used as pozzolanic materials in various forms [5, 6]. Mineral

admixtures as partial replacements of cement improve the mechanical and durability properties of concrete [7].

In India, sugarcane production was about 300 million tons per year [8] and plenty of bagasse is available in sugar industry. Bagasse is partly used as fuel in sugar industry and the remaining was dumped in ground. Silica content present in the pozzolan reacts with the free lime during hydration and forms calcium silicate hydrate (CSH) [9]. During hydration process, formation of C-S-H gel improves properties of blended (cement and supplementary cementitious material) hardened concrete. However, hydration time is inversely proportional to the porosity, which also increases pore structure and permeability of mortar and concrete. The waste from agro-industry was burnt in incinerating temperature of below 700 °C for 1 h which converts the silica content of the ash into amorphous phase

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[10]. In order to achieve the required size, ash was grinded in laboratory ball milling. The grinded ash mixed with ordinary Portland cement produces blended cement. The characteristics of agricultural industry waste ash purely depend on the following process such as burning, maintaining constant temperature, drying and grinding.

The objective of the present study is to assess the performance of bagasse ash as supplementary cementitious material in mechanical and durability properties of high-performance concrete, as well as to make out the optimal level of replacement.

2 Materials

2.1 Cement and bagasse ash

OPC 53 grade was used for making high-performance concrete specimens. The bagasse ash used in the test was obtained from Gobichettipalayam, TN, India. Bagasse ash varied up to 20% by weight of cement. The used cement and bagasse ash have specific gravity of 3.15 and 2.18. Initial and final setting time of ordinary Portland cement is found to be 80 min and 150 min with 29.5% standard consistency. The chemical composition of the cement and the bagasse ash is shown in Table 1.

2.2 Aggregate

Coarse aggregate in surface dry condition of size confirming to 20 mm was used. River sand was used as fine aggregate in saturated surface dry condition. Coarse aggregate and fine aggregate specific gravity is found to be 2.85 and 2.66. Water absorption of coarse aggregate and fine aggregate was 0.85% and 3.09%, respectively. All the aggregates were conforming to IS 383: 2016 [11] specifications.

2.3 Super plasticizers

The properties of super plasticizer were given as polycarboxylic ether-based super plasticizer, colour—light brown, and specific gravity— 1.08 ± 0.01 at 25 °C, $\text{pH} \geq 6$. The dosage of super plasticizer is adopted is 10 L/m³ of concrete. It was primarily developed for application in high-performance concrete for reducing water content.

3 Experimental work

3.1 Mix proportion and casting of HPC specimens

M60 grade mix design was done as per the method proposed by Aitcin [12], a simple approach that follows ACI 211-1 standard practice. The mix proportions for all the specimens are given in Table 2. Cement content is 510 kg/m³ for the control specimen and 5%, 10%, 15% and 20% of cement are replaced by bagasse ash for the remaining mixes. The weight of fine aggregate and coarse aggregate is 809 kg/m³ and 1125 kg/m³, respectively. The water content of the mix and W/B ratio is 130 kg/m³ and 0.28. The dosage of the super plasticizer was adopted as 10 L/m³ of concrete. The mixes were designated as HPC-BA0 for control specimen and HPC-BA1–HPC-BA4 for bagasse ash-blended high-performance concrete.

Ordinary Portland cement was replaced with bagasse ash of proportions 5, 10, 15, 20% by weight of cement. Five different concrete mixtures including control mixtures were prepared with a water binder ratio of 0.28. Concrete was mixed for about 5 min in laboratory drum mixer. The details of the number of concrete specimens cast for the present study are as follows: cube specimens of size 150 mm of 30 Nos., cylindrical specimens of size 150 mm

Table 1 Chemical composition of cement and bagasse ash (%)

Parameter	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	Na ₂ O	K ₂ O	CaO	LOI
Cement	11.99	2.64	4.03	0.85	0.54	1.52	70.93	0.8
Bagasse ash	55.49	9.92	8.29	7.96	0.93	8.34	8.74	5.4

Table 2 Mix proportion

Mix no.	Bagasse ash (%)	Water binder ratio	Cement (kg/m ³)	Bagasse ash (kg/m ³)	Fine aggregate (kg/m ³)	Coarse aggregate (kg/m ³)	Super plasticizer (L)	Water (kg/m ³)
HPC-BA0	0	0.28	510.00	00.00	809	1125	10	130
HPC-BA1	5	0.28	485.85	24.15	809	1125	10	130
HPC-BA2	10	0.28	461.70	48.30	809	1125	10	130
HPC-BA3	15	0.28	437.55	72.45	809	1125	10	130
HPC-BA4	20	0.28	413.4	96.60	809	1125	10	130

diameter and 300 mm height of 30 Nos., prism specimens of size 100 mm × 100 mm × 500 mm of 30 Nos., cube specimens of size of 100 mm of 63 Nos., and disc specimens of size of 152 mm diameter and 62.5 mm thickness of 21 Nos. After 24 h of casting, the test specimens were demoulded and immersed in water for curing, till the age of test.

3.2 Mechanical properties

The cube compressive strength was calculated as per IS 518-2004 [13] for bagasse ash-blended high-performance concrete. Splitting tensile strength was carried out on bagasse ash-blended high-performance concrete cylinders as per IS 5816-2004 [14]. Prism specimens were cast to determine the flexural strength of bagasse ash-blended high-performance concrete. The test was carried out at the age of 7 and 28 days curing.

3.3 Durability properties

Saturated water absorption (SWA) tests were carried out on bagasse ash-blended high-performance concrete cube specimens as per ASTM C642 [15] at the age of 7 and 28 days curing. SWA of bagasse ash-blended HPC is used to assess of the pore volume or porosity in hardened concrete which is occupied by water in saturated condition. It represents, in saturated bagasse ash-blended HPC specimens, the amount of water which can be separated on drying. The porosity obtained from absorption tests is designated as effective porosity. The formula used to calculate the effective porosity: $(\text{volume of voids } (W_s - W_d) / \text{bulk volume of specimen } (W_s - W_{\text{sub}})) \times 100$, where W_s is weight of specimen at fully saturated condition, W_d is weight of oven-dried specimen and W_{sub} is submerged weight of specimen in water [16]. Sorptivity measures the rate of infiltration of water into pores available in concrete. The sorptivity values of bagasse ash-blended high-performance concrete specimens after 28 and 90 days were calculated using the formula $I = S \times T^{0.5}$, where I is absorption

per unit area (mm), S is sorptivity (mm/h^{0.5}) and T is the time elapsed [17]. The impact strength tests were carried out on bagasse ash-blended high-performance concrete specimens at the age of 28 days curing using drop weight testing device as per ACI Committee 544. 2R-89. By using hammer, tested bagasse ash-blended high-performance concrete cube specimens were broken into small pieces. Further, the small pieces were powered using laboratory ball milling and pulverizer. For all the mixes, processed powder sample was tested for alkalinity.

4 Results and discussion

4.1 Compressive strength

Compressive strength results of HPC mixes with bagasse ash (HPC-BA) at the age of 7, and 28 days curing is given in Table 3. The compressive strength of HPC mixes containing bagasse ash decreases at 7 days curing compared to that of conventional concrete. HPC mixes with bagasse ash HPC-BA1 and HPC-BA2 show improvement in the compressive strength at 28 days curing, which was up to 6% compared to the mix without bagasse ash (HPC-BA0). HPC-BA3 and HPC-BA4 specimens show decrease in the compressive strength of 10.5%, respectively. Thus from the results, it has been observed that the maximum compressive strengths were obtained for mixes HPC-BA2 (10%). Increase in the compressive strength may be due to reaction of bagasse ash with calcium hydroxide and formation of CSH gel [18]. The calcium silicate hydrate is the component which gains strength due to binding effect. Up to 10% replacement of cement with bagasse ash shows increased compressive strength. Addition of bagasse ash beyond 10% has no significant reaction with calcium hydroxide. Excess bagasse ash does not react or act as binder in HPC; hence, it reduces strength at 28 days curing. The variations of compressive strength of HPC mixes

Table 3 Mechanical properties of bagasse ash-blended HPC

Mix no.	CS (N/mm ²)		SPT (N/mm ²)		FS (N/mm ²)		% Increase in strength					
							CS		SPT		FS	
	7 days	28 days	7 days	28 days	7 days	28 days	7 days	28 days	7 days	28 days	7 days	28 days
HPC-BA0	48.60	65.20	4.32	4.41	7.65	8.12	–	–	–	–	–	–
HPC-BA1	43.50	67.40	4.62	4.98	7.82	8.29	10.49	3.37	6.94	12.92	2.22	2.09
HPC-BA2	38.40	68.50	5.14	5.52	8.12	8.37	20.98	5.06	18.98	25.17	6.14	3.07
HPC-BA3	34.85	59.30	4.26	4.32	7.35	7.52	28.29	9.04	1.38	2.04	3.92	7.38
HPC-BA4	29.00	58.35	3.35	3.76	7.19	7.30	40.32	10.5	22.4	14.73	6.01	10.09

CS compressive strength, SPT splitting tensile strength, FS flexural strength

containing 5–20% of replacement of cement by bagasse ash at different 7 and 28 days are shown in Fig. 1.

4.2 Splitting tensile strength

Splitting tensile strength values of bagasse ash-blended high-performance (HPC-BA) at different ages are given in Table 3. The variation of splitting tensile strength and the influence of bagasse ash are shown in Fig. 2. It can be observed from the results that up to 10% (HPC-BA2 and HPC-BA3) of bagasse ash, the splitting tensile strength increases [18]. The percentage increase in splitting tensile strength at the age of 7 and 28 days is 18.98 and 25.17, compared to the conventional concrete.

4.3 Flexural strength

Flexural strength results of bagasse ash-blended high-performance (HPC-BA) at different ages are shown in Table 3. High-performance concrete without bagasse ash (HPC-BA0) attains a flexural strength of 7.65 N/mm², whereas flexural strength increases up to 6.14% for the specimens of HPC-BA1 and HPC-BA2 compared to HPC mix without bagasse ash. Specimens HPC-BA3 and HPC-BA4 attains lower flexural strength compared to the mix without bagasse ash. The variations of the flexural strength are shown in Fig. 3.

4.4 Saturated water absorption

The saturated water absorption tests for various high-performance concrete blended with bagasse ash (HPC-BA) mixes at the age of 28 days curing was 1.75, 1.51, 1.21, 1.10 and 1.15%, respectively, as shown in Table 4, and at the age of 90 days, the water absorption values was around 1.57, 1.30, 1.15, 1.08 and 1.27%, respectively. The addition of bagasse ash with high-performance concrete mixes on the water absorption and the variation of saturated water

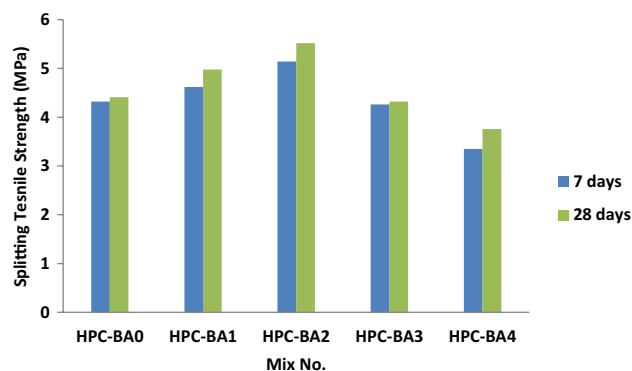


Fig. 2 Variation of splitting tensile strength

absorption with various proportions of bagasse ash are shown in Fig. 4. The optimum percentage of replacement of cement by bagasse ash was 15% for achieving the lowest values of SWA. Figure 4 shows that the bagasse ash-blended high-performance concrete mixes at the age of 28 days varies from 13 to 38% decrease in water absorption compared to with that of HPC without bagasse ash. The reduction in percentage of water absorbed is due to the filler effects of small pores in concrete and pozzolanic reaction between the blended materials which strengthened the surface morphology of concrete, bringing about fine and intermittent pore structure.

4.5 Sorptivity

The sorptivity values measured for HPC specimens at different ages of curing are shown in Table 4. From Fig. 5, it is experiential that the sorptivity of the HPC mixes containing bagasse ash was lesser when compared with that of HPC mixes free from bagasse ash. The reduction in sorptivity varies from 14.81 to 9.25% for different bagasse ash-blended high-performance concrete. It was observed

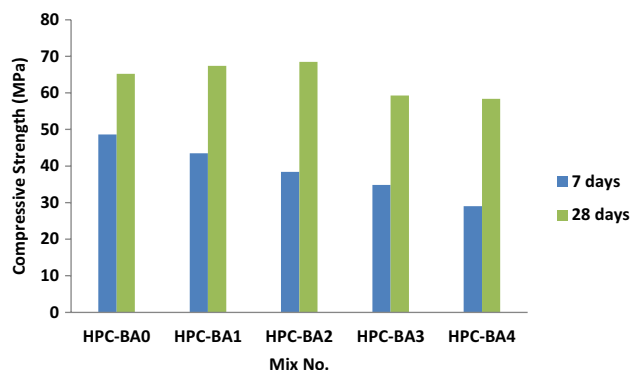


Fig. 1 Variation of compressive strength

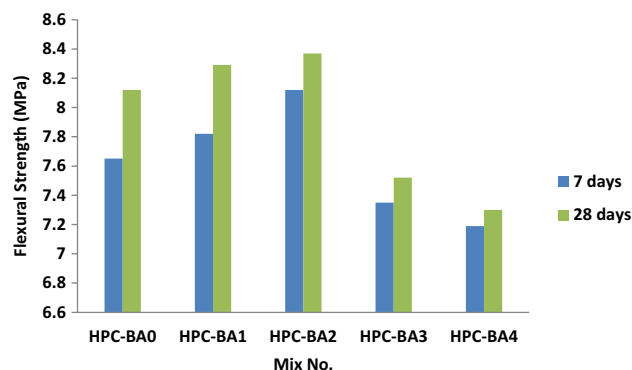
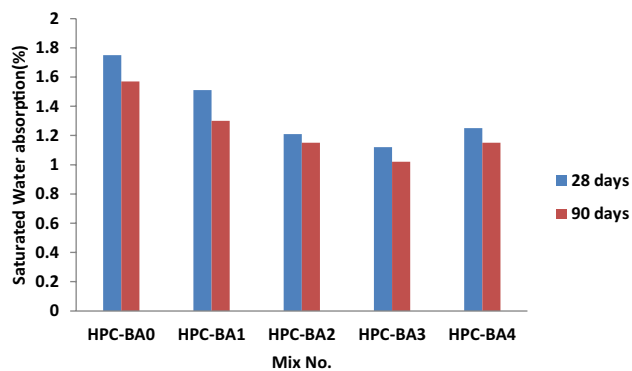
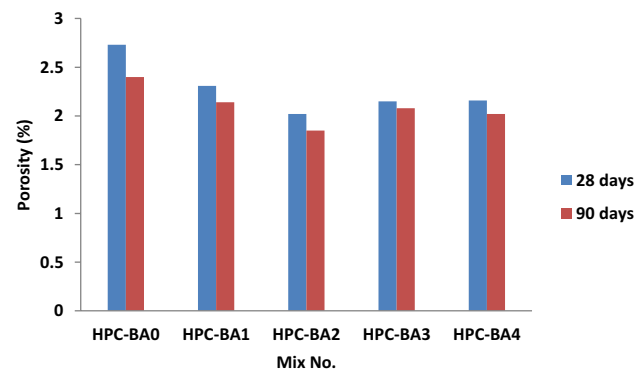
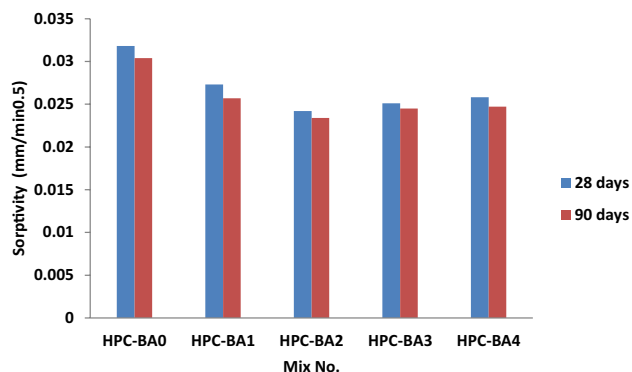


Fig. 3 Variation of flexural strength

Table 4 Durability properties of bagasse ash-blended HPC

Mix no.	SWA (%)		Porosity (%)		Sorptivity (mm/min ^{0.5})		Reduction compared to conventional concrete					
							SWA (%)		Porosity (%)		Sorptivity (mm/min ^{0.5})	
	28 days	90 days	28 days	90 days	28 days	90 days	28 days	90 days	28 days	90 days	28 days	90 days
HPC-BA0	1.75	1.57	2.70	2.40	0.0318	0.0304	–	–	–	–	–	–
HPC-BA1	1.51	1.30	2.30	2.25	0.0273	0.0257	13.71	17.19	14.81	6.25	14.15	15.46
HPC-BA2	1.21	1.15	2.20	2.10	0.0242	0.0234	30.85	26.75	18.51	12.50	23.89	23.02
HPC-BA3	1.10	1.08	2.35	2.15	0.0251	0.0245	37.14	31.21	12.96	10.41	21.06	19.40
HPC-BA4	1.15	1.27	2.45	2.20	0.0258	0.0247	34.20	19.10	9.25	8.33	18.86	18.75

**Fig. 4** Variation of saturated water absorption**Fig. 6** Variation of porosity**Fig. 5** Variation of sorptivity

that due to fineness of bagasse ash, water-level rise, due to which capillary action decreases in HPC [19].

The transformation of large pores into fine pores was achieved in fly ash-blended concrete due to the low permeability, which increases the pore reinforcement. Occurrence of pore reinforcement is due to the conversion of calcium hydroxide into calcium silicate hydrate gel by silica content (pozzolanic), which fills the large voids in hydrated cement and liberates some amount of calcium hydroxide. Similar pozzolanic reaction takes

place in BA-blended HPC, in which BA converts calcium hydroxide into calcium silicates. Thus, due to the effect of BA between cement paste phase and aggregate phase in transition zone, HPC gets lower permeability. Generally, transition zone is less dense in plain cement concrete than the cement paste and has minimum amount of crystal of calcium hydroxide, which gets reduced due to the addition of BA. The pores (micro and macro) present in HPC are filled by finer particles.

4.6 Porosity

The results of porosity study of concrete at 28 and 90 days are shown in Table 4. The porosities of concrete containing 15% and 20% of bagasse ash (HPC-BA3 and HPC-BA4) were higher than conventional concrete at the same period. It was observed that more the bagasse ash content, more the porosities of HPC. On the other hand, for the 10% of BA replacement (HPC-BA2), the fine particle size of pozzolan modified the pore structure and reduced the porosity of concrete. The variation in porosity of bagasse ash-blended high-performance concrete is shown in Fig. 6.

4.7 Impact test

The impact test results for 28 days are shown in Table 5. From Fig. 7, it is noted that the impact resistance of high-performance concrete mixes containing bagasse ash was more than that of HPC mixes without bagasse ash. Increase in the percentage of bagasse ash enhanced the impact resistance of HPC. This is because of the formation of certain quantity of constant C–S–H in high-performance concrete with bagasse ash.

4.8 Alkalinity measurement

The pH values of the aqueous solution prepared from HPC powder samples at 28 days curing are shown in Table 5. The HPC mixes containing bagasse ash showed lower value of pH compared to HPC mixes without bagasse ash. The variation of pH values is shown in Fig. 8. The concrete mixes containing bagasse ash showed lesser value of pH as compared to concrete mix without bagasse ash. The lower value of pH is due to lime consumption in pozzolanic reaction, and the free lime in concrete required to keep high pH in cement concrete is very low. Hence, there is no significant loss of alkalinity due to pozzolanic reaction between silica of bagasse ash and free calcium hydroxide of cement paste.

5 Conclusions

From the experimental work carried out, the following conclusions can be obtained.

1. The early compressive strength development may be due to the reaction of bagasse ash with CaO, which improves the hardening process in bagasse ash-blended HPC.

Table 5 Alkalinity measurement and impact strength of bagasse ash-blended HPC

Mix no.	pH value of samples (28 days curing)		Number of blows	Energy absorbed for ultimate failure (N m)
	pH meter	pH indicating papers		
HPC-BA0	13.40	> 13	180	3636
HPC-BA1	13.23	> 13	210	4242
HPC-BA2	13.16	> 13	224	4524
HPC-BA3	13.10	> 13	231	4666
HPC-BA4	13.05	> 13	238	4807

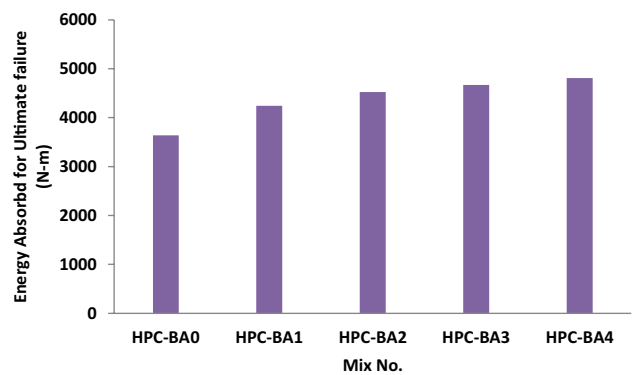


Fig. 7 Variation of impact strength

2. The splitting tensile strength increases gradually from 12.92 to 25.17% for the cement replacement of 5–10% of bagasse ash at the age of 28 days.
3. The flexural strength was increasing gradually from 2.09 to 3.08%, respectively, for the bagasse ash replacement level of 5–10%. Therefore, inclusion of bagasse ash improves strength properties of concrete up to 10%. Bagasse ash acts as micro-filler and improves the density of cement paste. The bond between the cement paste and the aggregate particles is enhanced and improves the concrete strength.
4. Due to the reduced permeable voids after 90 days of curing, the percentage of water absorption values of bagasse ash-blended HPC mix decreased reasonably.
5. Sorptivity of bagasse ash-blended HPC at 28 and 90 days curing gradually reduced with the increase in the bagasse ash content up to 20%, when compared with the control mix specimen.
6. The porosity of the HPC mixes varies from 2.20 to 2.70% at the age of 28 days. Similarly porosity varies from 2.10 to 2.40% at the age of 90 days. The porosity of the bagasse ash-blended HPC mixes was lower than the HPC mix without bagasse ash. Durability proper-

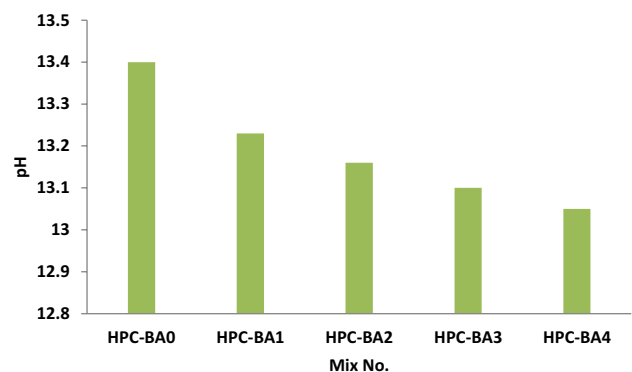


Fig. 8 Variation of alkalinity measurement

ties of HPC mixes blended with bagasse ash show significant improvement between 10% and 15% of replacement of cement.

7. Due to the formation of constant C–S–H in HPC mixes, impact resistance of bagasse ash-blended HPC mixes showed higher values compared to that of mixes without bagasse ash.
8. The pH values of HPC powder sample blended with bagasse ash showed lower value of 13.05 to 13.23 compared to sample without bagasse ash, where there is no loss of alkalinity significantly. The reduction in the pH is due to the presence of high magnesium content, which gradually replaces calcium hydroxide in HPC.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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