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Sustainable Reinforced Prestressed Alkali-Activated Concrete Beams Using Industrial Wastes: An Experimental Investigation

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Abstract

In an era where the sustainability of the construction industry is of prime importance, alternatives to cement are a matter of urgency. In the present time, Alkali-Activated Concrete (AAC) being a widely researched topic, offers a viable alternative to cement concrete as it has the potential to utilize industrial wastes as a source material. The current study delves into assessing the impact of prestressing force on both, reinforced AAC and reinforced ordinary cement concrete (OPCC) beams. Industrial wastes that serve as primary constituents for AAC include slag and fly ash, which, in the present investigation are activated using sodium-based activators. The concrete was developed using ambient curing with a compression value of 40 MPa to achieve sustainability. Analysis of deflection, load-carrying capacity and failure characteristics were conducted on the reinforced concrete beams in prestressed and un-prestressed states, encompassing both, reinforced AAC and reinforced OPCC beams. In comparison to reinforced AAC beams, OPCC beams had 18.9% higher strength in flexure, but the deflection was 53.3% higher for AAC beams with rebars. In prestressed condition, the reinforced OPCC beams had 22.5% more load-carrying capacity as compared to reinforced prestressed AAC beams, though reinforced prestressed AAC beams had 26.2% more deflection as compared to reinforced OPCC beams. Hence, sustainable reinforced concrete beams can be manufactured from industrial waste, having very good flexural behaviour and load-carrying capacity.

1. Introduction

Today's modern world, which is characterized by swift industrialization and an increasing demand for expedited infrastructure advancement, the construction sector is witnessing a significant upsurge. Concrete is considered to be the most versatile and popularly utilized construction material in contemporary society. Cement, the second most used building material, is now one of the most inevitable materials in the modern world, used in concrete mainly as binding material. Huge demand for cement exists in the construction sector, especially in developing countries like India. It is estimated that nearly 550 million tons of cement will be required in 2020 due to the rapid growth in the industrial and construction sectors. This means there will be more consumption of raw materials like limestone, a larger requirement of energy for various processes involved in the production of cement, and a higher emission of gases in the atmosphere [1]. It is estimated that a ton of cement production releases nearly 0.8 to 0.9 tonnes of carbon dioxide and other poisonous gases into the atmosphere. This makes cement production unsustainable and does not meet today's modern standards of greenhouse gas emission. Also due to rapid industrialization, huge amounts of industrial wastes are generated which do not have a proper method of disposal leading to pollution of land, water and air. One of the methods to achieve sustainable development and minimize pollution is to reuse the industrial wastes produced in large amounts in the construction industry.

This should be done judiciously so that alternatives to existing materials that are dependent on natural resources for its production can be developed. One of the construction materials whose alternative is needed is cement. A few alternatives for cement like geopolymer cement, magnesium oxycarbonate cement, super sulphated cement, and calcium sulphoaluminate cement, are being researched and have the potential to replace cement in the construction sector.

Alkali-activated concrete (AAC) also known as sustainable or green concrete, focuses on the utilization of industrial waste as its basic raw material and hence is widely researched and has found a lot of applications in the construction industry. It consists of a reaction between any material that is rich in silicate and aluminate material reacting with alkaline activators like hydroxide and/or silicates of sodium or potassium to form stable compounds. Researchers like Davidovitis, Hardjito et al., Jaarsveld et al. and Kumar et al. have used various materials like metakaolin, fly ash, slag, and red mud to name a few as source materials in preparing AAC [2], [3], [4], [5]. Durability properties like resistance to acid attack, sulphate attack, alkali-silica reaction and resistance to fire have been evaluated by many researchers, and it is observed that AAC has superior performance when compared to ordinary Portland cement concrete (OPCC) [6], [7], [8], [9]. Geopolymer bricks, lightweight blocks, foamed concrete, precast pipes, and railway sleepers have been developed and have equivalent mechanical and superior durability properties. Similarly, a structural assessment of geopolymer concrete (GC) was performed by Mo et al. [10]. Researchers have observed that structural members like columns, slabs, beams, and panels cast from GC showed no detrimental effect under various conditions. Due to the identical behaviour of GC and OPCC under load-bearing mechanisms, GC can be used to design members according to the codal provisions. Raj et al. [11] carried out a comprehensive review of the use of various materials that can be used to develop a mixture of proportions for the precast and prestressed methods adopted for railway sleepers. Rail seat deterioration, longitudinal cracking, and impact loading failure were listed as influential parameters for concrete sleepers. According to the authors, materials like polymer composite, fibre-reinforced concrete, GC, and concrete with rubber have great potential in railway sleeper production. Muthuramalingam et al. [12] used fly ash activated with sodium activators to cast prestressed electric concrete poles. Experimental investigation revealed that the poles made with GC had more deflection and increased load-carrying capacity as compared to poles cast with OPCC poles. Shojaei et al. [13] in their research work developed a mixture design of GC with GGBFS activated with sodium activators. Concrete sleepers made from GC were able to sustain the prestressing force and said mixture design confirmed EN 13230 standards. Deivabalan and Tamilamuthan [14] developed an M50 grade of concrete using fly ash as a source material by steam curing to produce concrete for rail sleepers, confirming Indian Railway Standard specifications. Monotonic loading was applied to sleepers produced from GC and OPCC. GC had more crack distribution and strength compared to sleepers made from OPCC. Neupane and Hadigheh developed a GC of M50-grade concrete for prestressed concrete beams using sodium silicate and sodium carbonate as activators to activate fly ash and slag. One of the comparisons showed that GC beams had 20% more flexural strength than OPC concrete beams. A numerical comparison using the Finite Element Method was also carried out for prestressed GC beams and OPCC beams, and the results of short-term deflection for both beams were nearly the same [15], [16], [17], [18]. Khan et al. [19] developed a mixture design of M60 grade for reinforced prestressed concrete sleepers using GGBFS and copper slag with alkaline activators. Railway sleepers were prepared according to Indian Railway standard specifications, and steam curing was adopted to achieve the required strength for geopolymer concrete. Sleepers made from GC were found to exhibit a greater yield load and ultimate load when compared with OPC sleepers. In GC beams, when M sand was replaced with copper slag, a higher strength was achieved. Thakkar et al. studied prestressed unreinforced GC beams and compared their behaviour with unreinforced prestressed OPCC beams. A greater deflection was observed in beams with GC compared to OPCC [20].

The strength gain mechanism of GC or AAC is hugely dependent on the method of curing. Most of the researchers have used steam or oven-curing techniques, which are difficult to implement in the field and for mass production. Very few studies have been carried out using ambient curing techniques, especially for prestressed concrete work. The performance of the prestressed reinforced AAC beams and its differences with the prestressed reinforced ordinary cement concrete beams, both, of M 40 grade concrete is carried out in the current investigation.

2. Experimental Program

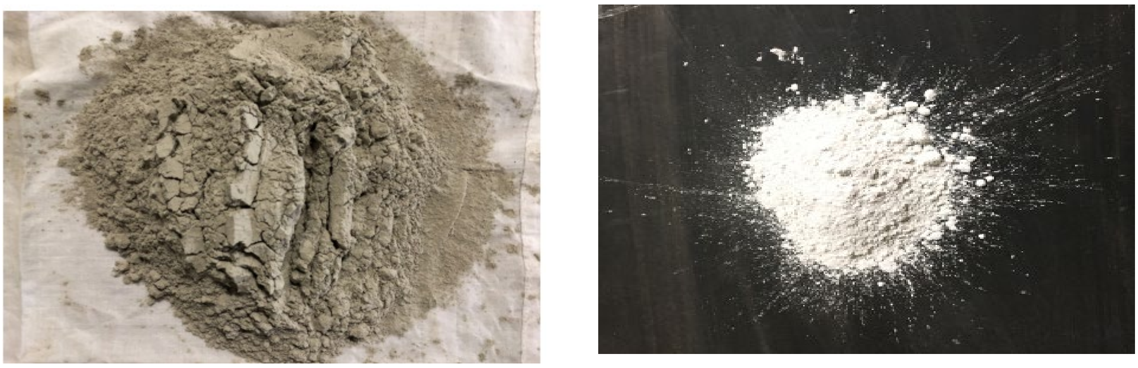
AAC and OPCC used for experimental investigation have a 28-day strength of 40 MPa after compressive loading.

2.1 Materials Used

The materials utilized in producing AAC consisted of a mixture of pulverised fly ash and slag (GGBFS). The representation of the chemical composition of the precursor materials is enlisted in Table 1. The fly ash used was procured from a local thermal power plant located in Ahmedabad, Gujarat, and it was confirmed to meet IS 3812 [21] specifications, while GGBFS was procured from JSW cement works near Surat, Gujarat and it was confirmed to meet IS 12089 [22]. Figure 1, shows the photographs of precursors that were utilized in the investigation.

Table 1 *Chemical characteristics of both the source material*

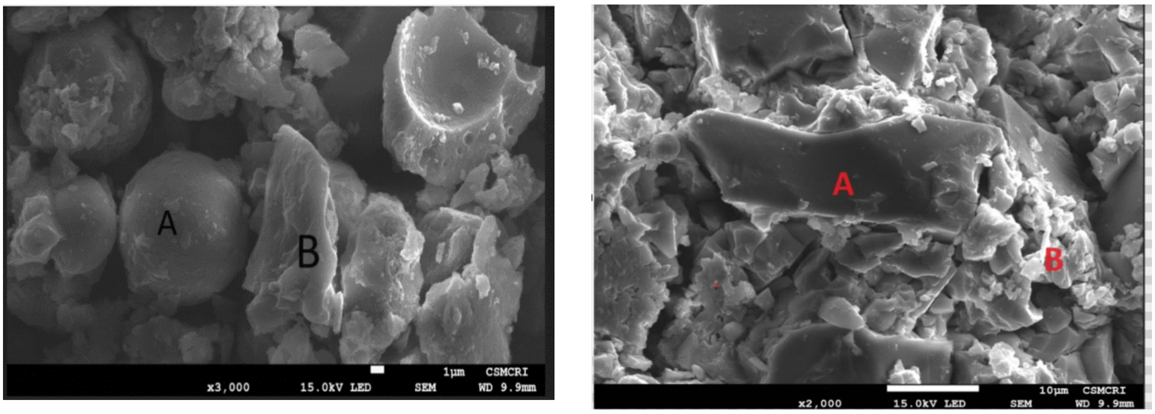
Material	Color	SiO_2	Al_2O3	Fe_2O_3	CaO	Retention on 45µm	Loss on Ignition	Pozzolanic Activity Index
Fly Ash	Light Grey	61.4 %	31.8 %	0.5 %	1.2 %	19.24 %	0.4 %	86.5 %
GGBFS	White	36.8 %	17.1 %	0.9 %	37%	11.0 %	0.6 %	90.9 %



(a) **(b)**

Fig. 1 *Industrial wastes (a) Fly ash; (b) GGBFS*

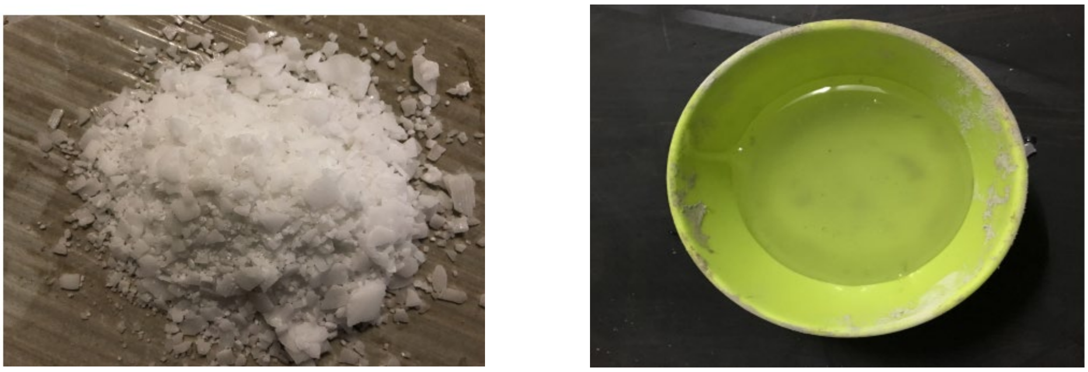
Low calcium fly ash had spherical shape particles while GGBFS had rhombus shape particles as observed in Figure 2.



(a) **(b)**

Fig. 2 *Scanning electron microscope images (a) Low calcium fly ash; (b) GGBFS*

The alkaline solution consisted of a blend of NaOH flakes mixed in water for the required molar concentration and water glass (Na_2SiO_3). Flakes form of NaOH with 98% purity, 1% chloride, and 0.005% nitrate content were used for AAC. NaOH was dissolved in tap water a day before concrete casting was carried out in the required molarity. As a lot of heat is liberated when NaOH flakes are dissolved, the solution is generally prepared a day before the casting. Na_2SiO_3 was in the form of a thick liquid with 36.6% SiO_2 and 16.7% Na_2O and had a bulk density of 1.66 gm/cc. Industrial-grade NaOH and Na_2SiO_3 were used for investigation as shown below in Figure 3.



(a) (b)

Fig. 3 *Alkaline activators (a) NaOH flakes; (b) Sodium silicate solution*

Coarse aggregates consisted of locally available natural stones of 20mm and 10 mm in a ratio of 60:40. The coarse aggregates used in this study had a specific gravity of 2.79 and 2.65, respectively, for sizes of 20 mm and 10 mm, while Fineness Modulus was 7.38 and 6.35, respectively. The water absorption in 10 mm and 20 mm downsize aggregates were 0.97% and 1.25%, respectively. Fine aggregate consisted of locally available sand. Sand with a specific gravity of 2.7 and a fineness modulus of 3.1 according to specifications of IS 383 [23] was used. Naptha-based superplasticizer from BASF was used in both concretes to obtain the required workability. The beams were reinforced with bars of Fe 415 grade of steel.

In the case of prestressed beams, for both, reinforced AAC and OPCC, high-strength steel bars were used for prestressing. The prestressing force was applied using high-strength steel wires, which were 3 mm in diameter and 3 ply. The wire had 0.6 to 0.85% Carbon, 0.78 to 1% Manganese and 0.05% Sulphur and confirmed to specifications of IS 1343: 2012[24].

2.2 Mix Design and Casting Procedure

Due to the non-standardization of the mixture design for AAC, numerous experimental mixtures were conducted to achieve strength under compressive loading of 40 MPa in ambient curing for AAC at 28 days. After various trial combinations with changing the ratios of the precursors, it was found that an equal amount of both the source materials gave the required compressive strength in AAC at ambient curing conditions.

Similar to OPCC in AAC, the first mixing of aggregates, both, coarse and fine, was done for 3 -4 minutes. After the addition of source materials, i.e., fly ash and GGBFS, dry mixing was again carried out for 5 more minutes. After this, the addition of an alkaline solution in the form of NaOH and Na_2SiO_3 was carried out in the dry mixture. Subsequently, the addition of a superplasticizer was done in the required dosage. As the mixture of AAC concrete has less workability, hence some quantity of water was further added to it. This is called extra water and is generally 10-15% of the source material. A slump of 100 mm was achieved for both the concrete. OPCC was designed as per IS 10262: 2019[25]. The mixture design for AAC and OPCC is represented in Table 2. Table 3, represents the strength of compression of OPCC and AAC at various ages.

Table 2 *Mix design of OPCC and AAC*

Material type (kg/m^3)	OPCC	AAC
Cement	399	-
Fly Ash	-	214.3
GGBFS	-	214.3
Coarse Aggregate: 20 mm	705	750.3
Coarse Aggregate: 10 mm	468	503.1
Sand	630	668
NaOH solution	-	48.9
Water glass	-	122.4
Extra Water	177.3	36
Superplasticizer	3.94	4.3

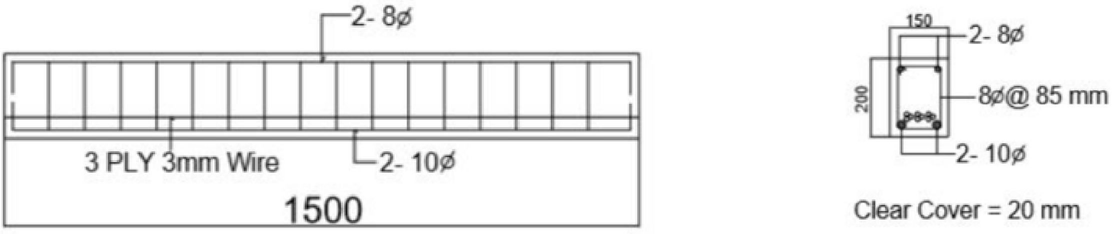
Table 3 *Average strength of compressive load at curing ages*

Name of Specimen	Compressive Strength (MPa)		
	3 days	7 days	28 days
OPCC	19.9	32.9	47.3
AAC	21.4	33.2	47.6

2.3 Casting of Beam Specimens

Four reinforced concrete beams, each of AAC and OPCC were cast to enable a comparative study. Out of the four beams, two beams of AAC and OPCC were applied with prestressing force. Beam dimensions of 1500 x 150 x 200 mm were cast using AAC and OPCC.

The beams were reinforced on the section that will experience tension with two bars having 10 mm diameter, while another 2 rods having a diameter of 8 mm were used as anchor bars. The stirrups were placed at 85 mm c/c throughout the beams. High-tensile-strength (HTS) bars were pre-stretched by 12 mm before casting in the beams where the prestressing force was to be applied as per the design calculations. Figures 4 and 5 show the cross-section of beams, placement of reinforcement and application of prestressing force. LVDT and dial gauges were placed at critical points to measure the displacement of beams at various points. Figure 6 shows the set-up of LVDT and dial gauges.



(a) **(b)**

Fig. 4 *Beam detailing (a) Cross section; (b) Reinforcement detailing of non-prestressed concrete beams*

(a) **(b)**

Fig. 5 *Set up of reinforcement and for application of prestressing force (a) Enlarged view; (b) Zoom-out view*

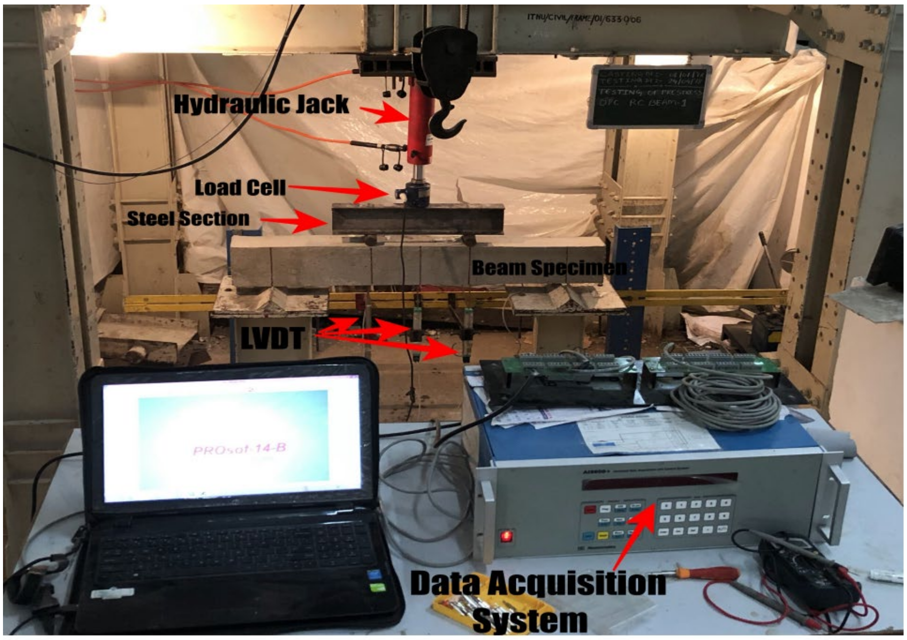


Fig. 6 *LVDT and data acquisition system*

3. Results and Discussion

3.1 Behaviour of Non-Prestressed Reinforced AAC and OPCC Beams

Non-prestressed reinforced OPCC beams were named Ordinary non-prestressed reinforced concrete (ONPRC)1 and ONPRC2. When subjected to loading, the ONPRC1 and ONPRC2 carried 85 kN and 84 kN loads while showing deflection of 13.4 mm and 12.4 mm. The maximum value of strain in compression on the surface of concrete in ONPRC1 was 0.00195 while in ONPRC2 it was 0.00199 at peak loads. ONPRC1 had a maximum strain of 0.00049 on the top side, 0.00341 of strain at the bottom centre and 0.00281 of strain on both sides. In the case of ONPRC2, the strain on the top side, bottom center, and at sides was 0.00047, 0.00466, and 0.00145 respectively. Cracks that were primarily seen on ONPRC1 and ONPRC2 were at 54 kN and 52 kN respectively. Figures 7 and 8 show the displacement at various locations for ONRPC1 and ONRPC2 beams, while Figure 9 shows the failure of ONRPC1 beam. The reinforced concrete beam developed severe cracks at centre before failure.

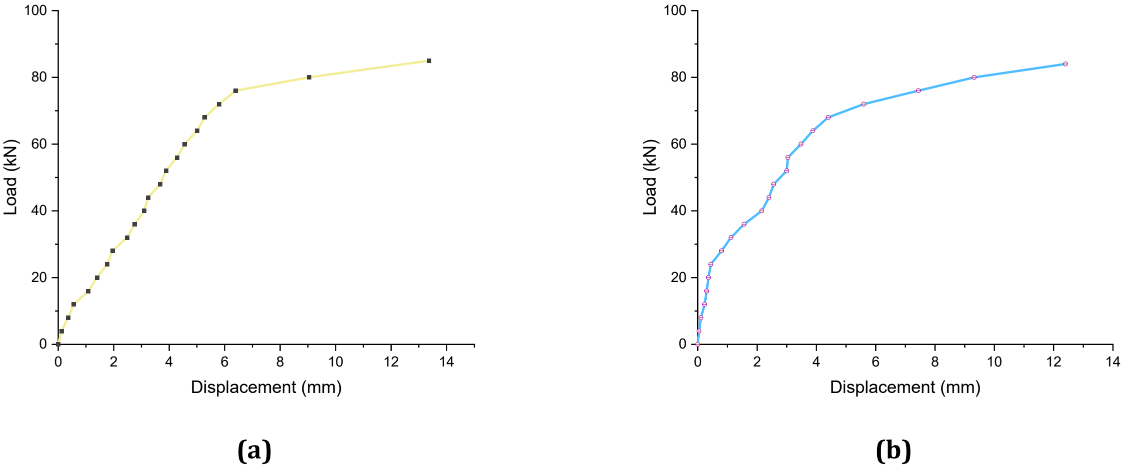
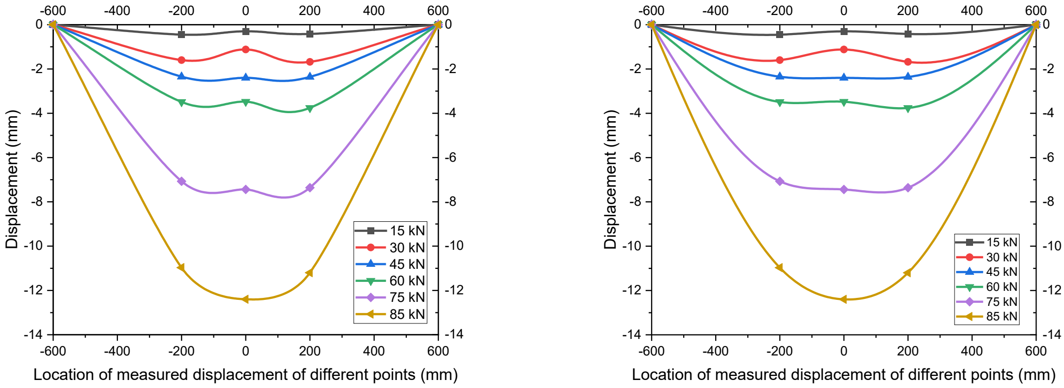


Fig. 7 *Load vs displacement graph (a) ONPRC1; (b) ONPRC2*

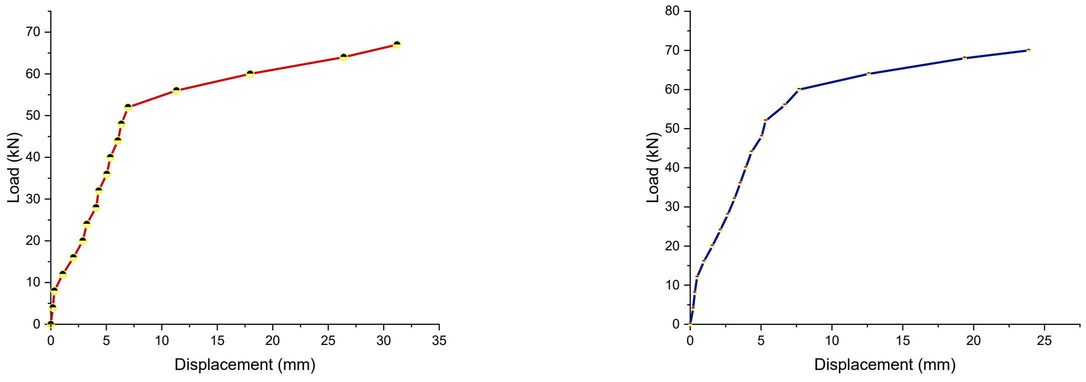


(a) **(b)**

Fig. 8 *Displacement v/s location of displacement at various positions (a) ONPRC1; (b) ONPRC2*

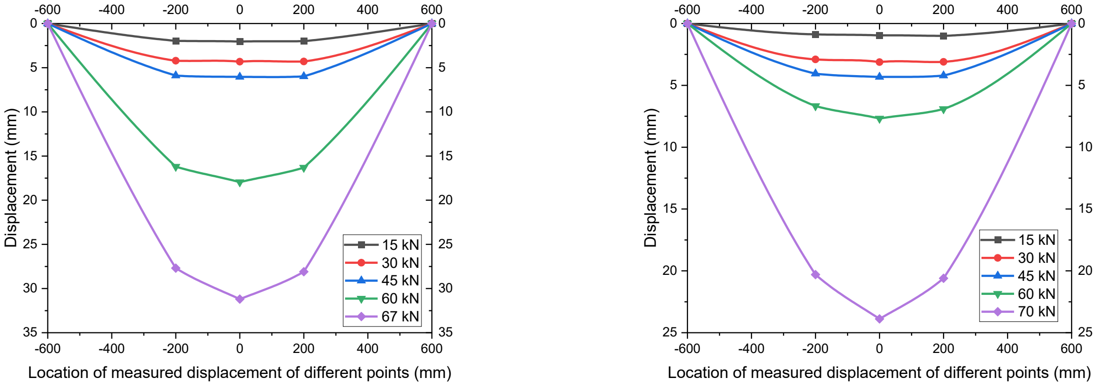
Fig. 9 *Failure of ONPRC beam*

Reinforced AAC beams without prestressing force were denoted as AACNPRC1 and AACNPRC2. Both the beams had a load-carrying capacity of 67 kN and 70 kN, respectively, with total deflection of 31.2 mm and 23.88 mm in each beam, at failure load as shown in Figures 10 and 11. Maximum peak compressive strain in concrete at the top surface in beam AACNPRC1 was observed as 0.00267, while in the case of AACNPRC2, it was observed to be 0.00336. When AACNPRC1 was subjected to a 50 kN load, it experienced its first crack, which measured 0.00187 at the top, 0.00418 at the bottom, and 0.00283 at the side. Figures 10 and 11 represent the load-deflection curve when the first crack for AACNPRC2 developed at 52 kN had a top compressive strain of 0.00272, a bottom strain of 0.00308, and a side strain of 0.00092.



(a) **(b)**

Fig. 10 *Load v/s displacement graph (a) AACNRPC1; (b) AACNRPC2*



(a) **(b)**

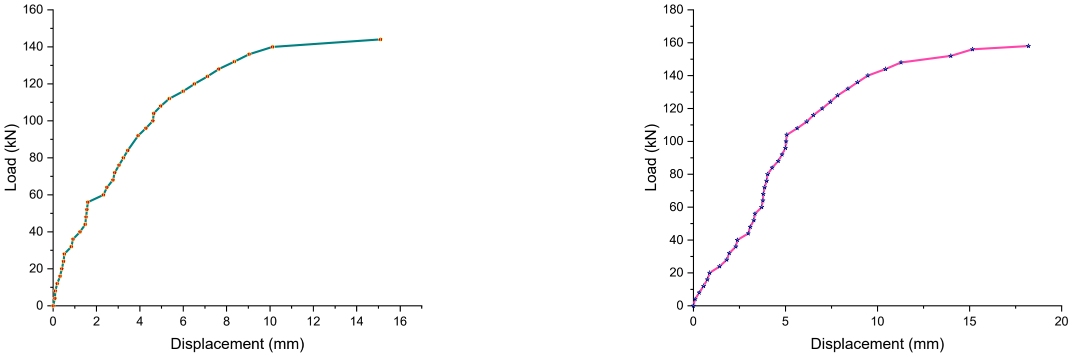
Fig. 11 *Displacement v/s location of displacement at various position (a) AACNPRC1; (b) AACNPRC2*

Fig. 12 *Crack pattern in GNRPC beam*

Alkali-activated reinforced non prestressed concrete beam also cracked from the bottom, but unlike ordinary concrete beams, it developed hairline cracks at the bottom surface and did not show severe failure (Figure 12).

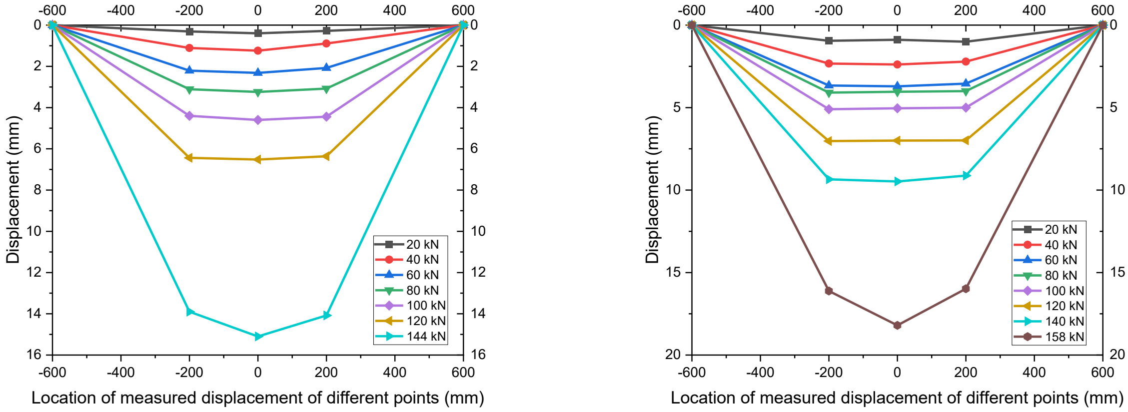
3.2 The Behaviour of Prestressed Reinforced AAC and OPCC Beams

OPRC1 and OPRC2, which were prestressed reinforced ordinary cement concrete beams, demonstrated load-carrying capacities of 144 kN and 158 kN, respectively. Figure 13 illustrates the deflections, which were 15.1 mm for OPRC1 and 18.2 mm for OPRC2. With strain values of 0.00128 at the top centre fibre, 0.00404 at the bottom centre, and 0.00312 at the bottom side, the first crack for OPRC1 manifested at 106 kN load. After failure, many cracks were seen on the bottom surface notwithstanding the first crack. The top concrete surface of the OPRC2 specimen showed a maximum compressive strain of 0.00321 at load of 158 kN. When the first crack appeared, the top centre strain was measured at 0.0018, while the bottom centre and bottom side strain measurements were -0.00407 and -0.00440, respectively in OPRC2 beam. First flexural crack in OPRC2 was noticed at 112 kN. Figure 14 and 15 show the displacement and its location and cracking pattern in OPRC2 beam.



(a) **(b)**

Fig. 13 *Load v/s displacement graph (a) OPRC1; (b) OPRC2*

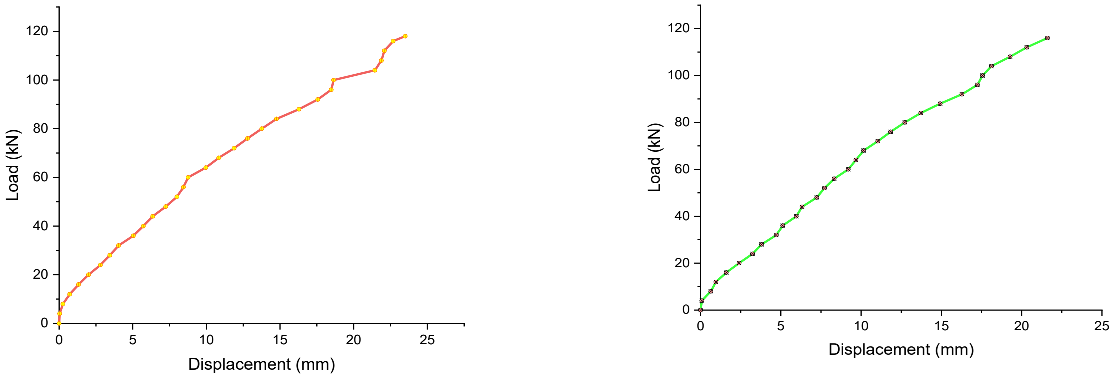


(a) **(b)**

Fig. 14 *Displacement v/s location of displacement at various positions (a) OPRC1; (b) OPRC2*

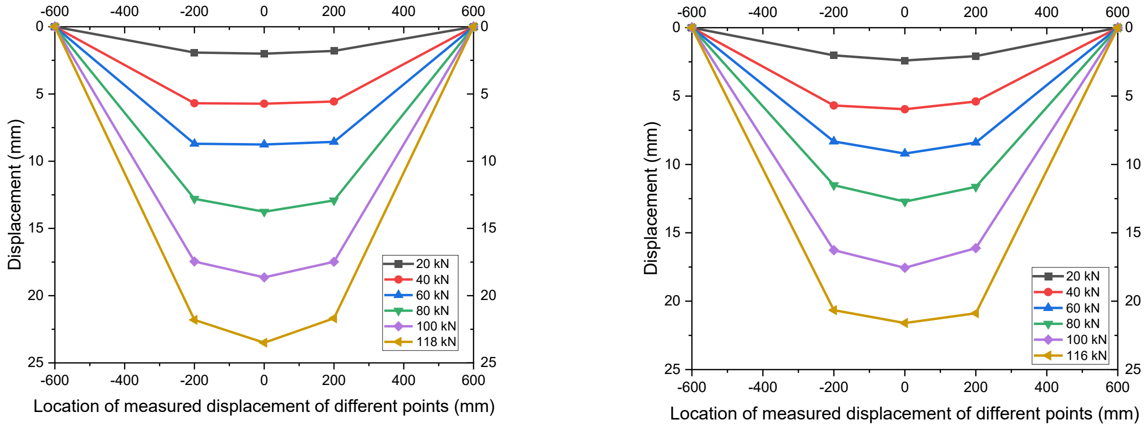
Fig. 15 *Crack pattern in ordinary prestressed reinforced concrete (OPRC) beam*

Reinforced prestressed AAC beams were denoted as AACPRC1 and AACPRC2. The flexural load at which the failure of AACPRC1 and AACPRC2 occurred was 118 kN and 116 kN respectively. Total deflection at the centre of the beam at failure was 23.5 mm and 21.6 mm, respectively, for AACPRC1 and AACPRC2, depicted in Figure 16. Under a load of 118 kN, the top concrete surface of the AACPRC1 specimen showed a maximum compressive strain of 0.00233. The strain of 0.003 was observed at the centre top, while the strain at the central section at the bottom was -0.00654. The strain observed at the side section of the bottom was noted to be -0.00233 when the first crack was visible. The AACPRC1 specimen developed many cracks during testing, which caused the beam to fail in flexural. The first crack developed at 95 kN load. At a load of 116 kN, the top concrete surface of the AACPRC2 specimen recorded a maximum compressive strain of around 0.00242. The top centre strain, the bottom central and side strains were noted to be 0.00282, -0.01100 and -0.00696 in AACPRC2 beam. As seen in Figure 17, the first crack in the AACPRC2 beam appeared at a load of 92 kN. Multiple cracks can be seen at the bottom of the reinforced prestressed AAC beam in Figure 18.



(a) **(b)**

Fig. 16 *Load v/s displacement graph (a) AACRPC1; (b) AACRPC2 beams*



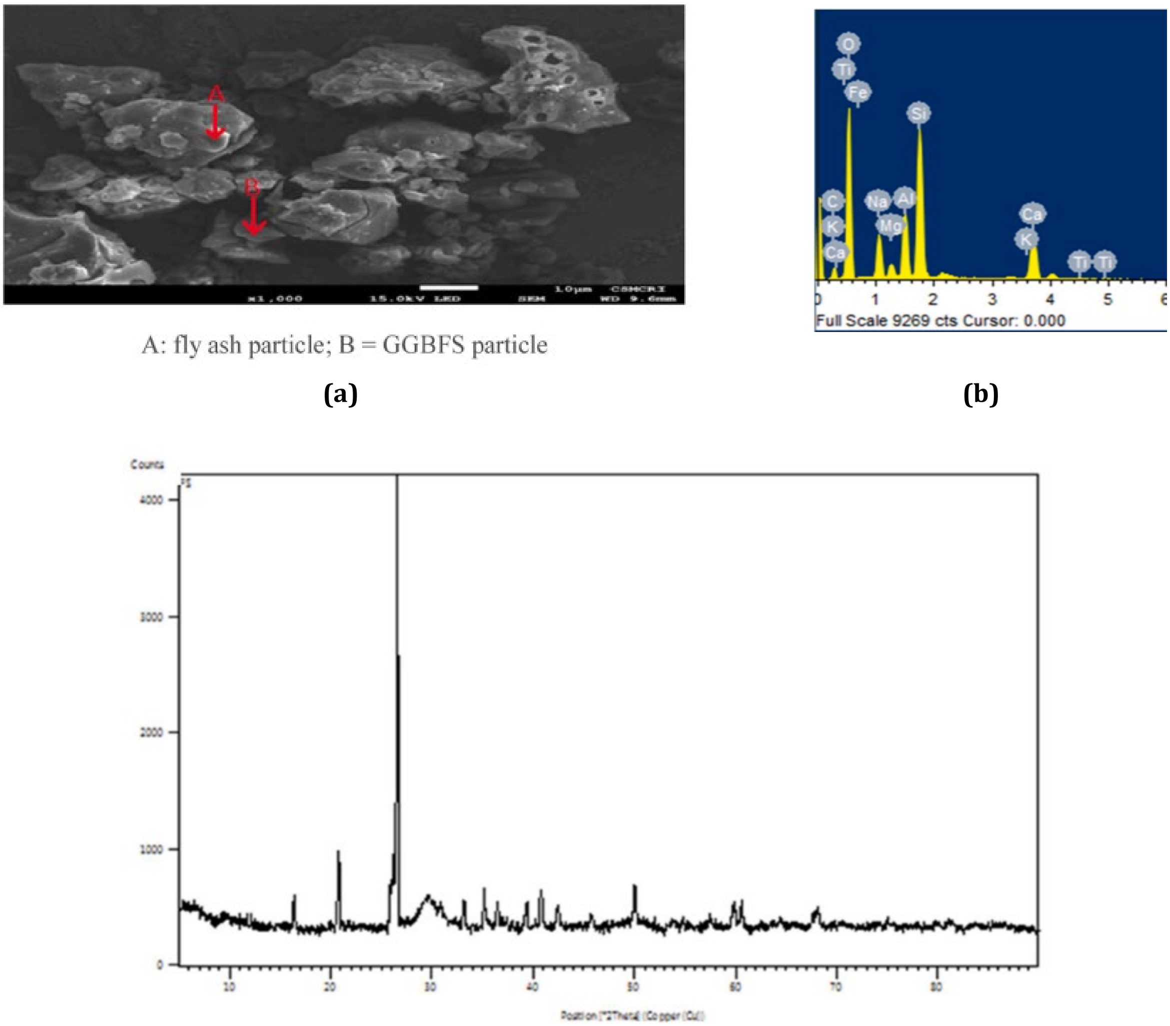
(a) **(b)**

Fig. 17 *Displacement v/s location of displacement at various positions (a) AACRPC1; (b) AACRPC2*

Fig. 18 *Crack pattern in AACRPC beam*

4. Microstructure Studies of AAC

As observed in the EDAX analysis, there is the presence of oxides of Si, Ca, Na, Al, Fe and K, while the presence of mullite, quartz, and hematite are indicated from XRD results. SEM image of the paste shows that both fly ash and GGBFS formed calcium alumino-silicate hydrate gel, which imparts strength at ambient curing in AAC.



A: fly ash particle; B = GGBFS particle

(a)

(b)

(c)

Fig. 19 *Microstructure of AAC concrete (a) Scanning electron microscopic image of AAC paste; (b) EDAX of Fly ash; (c) XRD pattern of AAC paste*

5. Conclusion

An ambient curing technique can be used to manufacture sustainable alkali-activated reinforced concrete beams which can sustain the prestressing force and can undergo appreciable deformation.

- The average load at which cracks developed in reinforced concrete beams without the application of prestressing force in OPCC was 84.5 kN while in AAC was 68.5 kN. Thus, reinforced non-prestressed beams of OPCC had 18.9% more load-carrying capacity compared to AAC beams.
- Non-prestressed reinforced concrete beams of OPCC and AAC had an average deflection of 12.88 mm and 27.54 mm. Thus, the deflection of the AAC beams was greater than the OPCC beams by 53.23%.
- The load-bearing capacity of the reinforced prestressed concrete beams built with OPCC was 151 kN, whereas the average capacity of beams made with AAC was 117 kN. This suggests that the ultimate load-carrying capability of OPCC beams is 22.51% higher than that of AAC beams.
- The average deflection of the OPCC beam is 16.65 mm, while the average deflection of the AAC beam is 22.55 mm. The deflection of the AAC beam is greater than OPCC beams by 26.16%

Thus, concrete made from industrial waste like fly ash and GGBFS can be effectively used as reinforced prestressed alkali-activated concrete under ambient curing conditions and shows good load-carrying capability and deflection making it possible for real-life application in the construction industry.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The contributions of all authors must be described in the following manner:
The authors confirm their contribution to the paper as follows: ***study conception and design:*** *Darshan Bhatol, Sonal Thakkar and Urmil Dave;* ***data collection:*** *Darshan Bhatol;* ***analysis and interpretation of results:*** *Sonal Thakkar, Darshan Bhatol;* ***draft manuscript preparation:*** *Abhishek Chanda* ***Supervision and Editing:*** *Urmil Dave* ***Revision and Editing of Manuscript:*** *Sonal Thakkar and Abhishek Chanda*
All authors reviewed the results and approved the final version of the manuscript.

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