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Flexural Behaviour of Reinforced Concrete Beams using Alkali Activated Binders

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Abstract: This article discusses several different percentages of alkali activators that can be used in place of conventional cement with ground granulated blast furnace slag (GGBFS) resulting in alkali activated binder (AAB). They are labelled as G10 percent, G7 percent, G6 percent, and G5 percent, respectively, since they include 90 percent, 93 percent, 94 percent, and 95 percent of GGBFS, as well as 10 percent, 7 percent, 6 percent, and 5 percent alkali as an activator, respectively. A comparison of specimens formed of reinforced beams utilising alkaline binders and conventional cement is shown in this study. One of the six varieties of reinforced concrete beams is composed of Portland slag cement, four of the beams are cast with varied chemical concentrations of AAB concrete, and the last beam is produced with Ordinary Portland cement. They are examined using four-point bend test. The behaviour of reinforced concrete beams composed of AAB and conventional cement is analysed in this study, and the crack types and ultimate loads of failure are also demonstrated. It was established that the combination of alkali activated binders known as G10 percent was the most successful one since it led to good performance when compared to the OPC concrete.

Keywords: Ground granulated blast furnace slag, alkali activator, alkali-activated binder, conventional cement, ultimate flexural strength

1. Introduction

Cement is a material that brings ease to construction. Cement is used to produce mortar and concrete that are versatile. As a result, cement is accepted worldwide and it has become one of the essential construction materials. The consumption of cement accelerated sharply after 1945 [IS 455:1989]. The global cement consumption has increased 30 fold since 1950 and almost 4 fold since 1990 [Zhao & Sanjayan, 2011]. Concrete is based mainly on Portland cement, and it is the most widely used material on earth. As the consumption surges the environmental associated issues also increases. It is sufficiently known that cement production not an environmentally friendly industry due to the large amounts of CO_2 released because of the de-carbonation of $CaCO_3$. Cement production consumes approximately 5% of the worldwide industrial energy while producing each ton of OPC demands about 1.5 tons of raw materials. The cement industry is solely responsible for roughly 7% of all CO_2 emissions throughout the globe [Pal, 2018]. Such developed condition creates an immense pressure on the scientific society to look for an alternative.

One possible alternative is the use of alkali activated binders. Generally, the alkali activated material is comprises of industrial byproduct and silicate. The most utilized industrial byproduct is fly ash (FA) and ground granulated blast

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furnace slag (GGBFS) due to their exceptional performance [Miyamoto et al., 2015; Balon et al., 1973; Nehdi et al.,2020; Yang et al., 2013; Zheng et al., 2020].Therefore, alkali-activated binders have the possible potential to replace conventional Portland cement as a green binder. The CO_2 emission reduced by 50-80% in the development of alkali activated binder.

The current study focuses bending behaviour of alkali-activated reinforced concrete beams. The activator is entirely new. It doesn't contain conventionally used sodium hydroxide, potassium hydroxide or any rich silica sources as major chemicals. The activator used in the current study is a composition of metal hydroxide, sulphate oxide and sodium oxide. The value of pH of A_2B (Metal sulfate) = 10, the pH of sodium hydroxide = 13.46 and the pH of equal combination of A_2B and Sodium Hydroxide =13.46.

2. Material Used

2.1 Ground Granulated Blast Furnace Slag (GGBFS)

GGBFS is as industrial by product of iron industry from blast furnace. It is produced when iron is extracted from hematite and magnetite. It is non-toxic by product and dumped directly in nature hence termed as waste. The GGBFS used in the development of binder is procured from Tata Steel Ltd.at Jamshedpur, [IS 12089: 1987]. The procured GGBFS is in pellet form and hence turn into powdered from to use it as binder. The detail chemical composition is reported in Table1, and physical properties are mentioned in Table 2.

2.2 Portland Slag Cement (PSC) and Ordinary Portland Cement (OPC)

The PSC used in the investigation is procured from Lafarge Holcim under the brand name of Lafarge. The conventional PSC has been used for the comparative study. The details regarding the chemical composition are mentioned in Table 1 and physical properties are mentioned in Table 2. In the current study, the OPC 43 has also been used for comparison of results for the better understanding. Some of the details regarding the chemical composition is mentioned in Table 1 and physical properties are mentioned in Table 2.

Table 1 - Chemical composition of different binders

Compound	GGBFS%	PSC	OPC43
CaO	61.5	63.69	62.49
SiO_2	18.34	21.21	20.27
Al_2O_3	9.76	5.54	5.32
MgO	6.26	2.93	4.46
Fe_2O_3	1.32	3.11	3.16
SO_3	0.83	2.63	3.53
TiO_2	0.74	-	-
K_2O	0.36	0.71	0.65
MnO	0.15	-	-
Na_2O	0.14	0.18	0.12
P_2O_5	0.07	-	-
CeO_2	0.06	-	-
SrO	0.06	-	-

Table 2 - Physical property of conventional cement

Physical Requirements	PSC	OPC43
Specific Gravity	2.92	3.10
Standard Consistency	34%	33%
Soundness Le-Chatelier (mm)	1.5	2
Setting time initial (min)	68	65
Setting time final (min)	310	340

2.3 Alkali Activators Used

The activator is combination of metal hydroxides (MOH) and A_2B. The activator used in the present study is alkaline in nature. The combined pH of the activator is around 13. The major component of A_2B is SO_3 and Na_2O. The detail description of A_2B is mention in Table 3.

Table 3 - Chemical composition of alkali activator (A_2B)

Compound	A_2B%
CaO	0.08
MgO	0.12
Fe_2O_3	0.02
SO_3	80.3
K_2O	0.19
MnO	0.02
Na_2O	16.36
P_2O_5	0.02

2.4 Fine Aggregate, Coarse Aggregate and Water

The fine aggregates were procured from the Kharkai River, and the physical properties are as per Indian standard, [IS 383:2016]. The fine aggregate is of zone II and some of the details regarding the physical properties are given in Table 4. The coarse aggregate used in this experimentation obtained from Jamshedpur, Jharkhand of nominal size 20 mm and the details of physical properties are tabulated in Table 4. Potable water was used for casting and curing of all the concrete specimens and the requirements are as per Indian standard, [IS 516:1959].

Table 4 - Physical properties of fine aggregate

Sl. No.	Properties	Fine aggregate	Coarse aggregate
1	Fineness modulus	2.83%	6.81%
2	Specific gravity	2.59	2.83
3	Free moisture	0.20%	0.10%
4	Water absorption	0.80%	0.35%
5	Bulk density (kg/m^3)	1560	1660
6	Bulking of sand	3%	N.A.

2.5 Mechanical Property of Binder

The mechanical property of the binder gives a clear indication about the binder could be used or not. In order to assess the mechanical property of binder mortar, mortar mix is prepared. The mortar mix is prepared in the ratio of 1:3. The water used to prepare the mortar is computed from $\left(\frac{P}{4}+3\right)$%. The mixing procedure is as per Indian standard [IS 516:1959]. After casting, the specimens were kept for curing and they were tested after 3, 7 & 28 days of curing.

3. Mix Proportions

According to IS 10262:2009 standards, the activated concrete's mixing ratio is similar to that of ordinary concrete. Alkali activated binder (AAB) has been developed with a slightly different mixing method than traditional binder. Alkali solution preparation takes place before mixing in activated binder. Table 5 provides information on the activator and GGBFS content in various types of mixes. AAB are classified as G10 percent, G7 percent, G6 percent, and G5 percent, respectively, since they include 90 percent, 93 percent, 94 percent, and 95 percent of GGBFS and 10 percent, 7 percent, 6 percent, and 5 percent alkali. Table 5 lists the mix proportions of the various materials used for producing AAB concrete. For all types of the specimen, the water content in prepared concrete is 177.44 kg/m^3. The activator is individually combined with water before producing the concrete. The activator and water are combined, and the mixture is continually stirred for 10 minutes to create a homogenous solution. For all varieties of the mix, the water to binder ratio stays the same at 0.48.

Table 5 - Details of mix proportions for different materials used in AAB concrete

RC beam nomenclature	Designated activator	Alkali (%)	GGBFS (%)	Alkali (kg)	GGBFS (kg)	Binder content (kg/m^3)	Sand (kg)	Aggregate (kg)
S240	G10%	10	90	3.70	365.98	369.68	665.13	1185.77
S230	G7%	7	93	2.59	367.09			
S225	G6%	6	94	2.22	367.46			
S220	G5%	5	95	1.85	367.93			
Note: The binder content for PSC and OPC 43 was same as 369.68 kg/m^3								

Table 6 - Specimens dimension

Sl. No	Specimen type	Size (mm)
1	Cube	150 x150 x 150
2	Cylinder	150 mm diameter x 300 mm height
3	Plain beam	100 x 100 x 500
4	Reinforced beam	1500 x 150 x 200

4. Mixing, Casting, Curing, and Testing

The mixing part was performed by tilting rotary drum. Initially, fine aggregate and binder were transferred to the rotating drum and they were allowed to get uniform mix. After achieving a uniform colour of the dry mix, coarse aggregate has been transferred to the existing mix to obtain a uniform dry mix. Again, after achieving the uniformity of the dry mix, the total estimated water was added gradually to obtain a consistent mix. Before transferring the fresh concrete mix in the moulds, it was cleaned and lubricated properly. The fresh concrete mix was then transferred to the various moulds of different dimensions as mentioned in Table 6 by providing proper compaction as per Indian Standards. After 24 hours, the cast specimens were de-moulded and they were kept in water for curing for desired period of maturity.

The used samples were in the shape of cubes, cylinders and prisms for testing of compressive strength, split tensile strength, and flexural strength of the concrete. The cube specimen was tested for compressive strength using a compression testing machine with a 3,000-kN capacity as shown in figure 1. The loading rate used in the compressive strength and split tensile strength tests was 140 kg/cm^2/min. and 1.2 N/mm^2/min to 2.4 N/mm^2/min as per code Indian standard, [IS 516:1959; IS 5816 (1999)], respectively. The samples were tested in different age of maturity (1, 3, 7, 28, 90, 180 and 365 days) under saturated surface dry condition. The flexural strength of prism is conducted by 4-point bending test. The experimental setup for load bearing capacity of reinforced concrete beam has been shown in Figure 2 which was conducted on the specimens of size as mentioned in Table 6 after 28 days of curing. For comparison, reinforced concrete beams were cast with PSC and OPC. The casting and curing procedure for all the type of binders are same. During the test, the data of the deflection, load and displacement have been recorded carefully. While conducting the test on the reinforced concrete beam, peak load and the corresponding pattern of the cracks and number of cracks have also been recorded.

Fig. 1 - Cube compressive strength testing setup

Fig. 2 - Experimental setup of reinforced concrete beam in bending

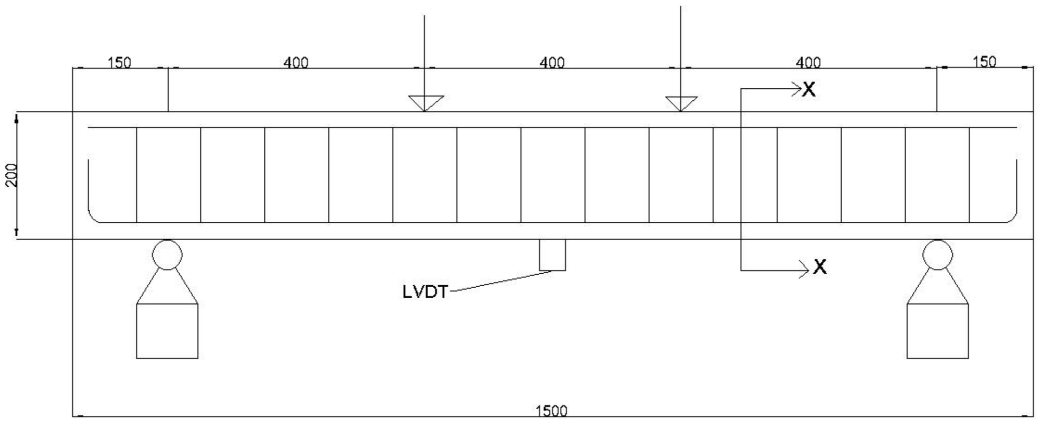


Fig. 3 - Schematic geometry of reinforced concrete beam

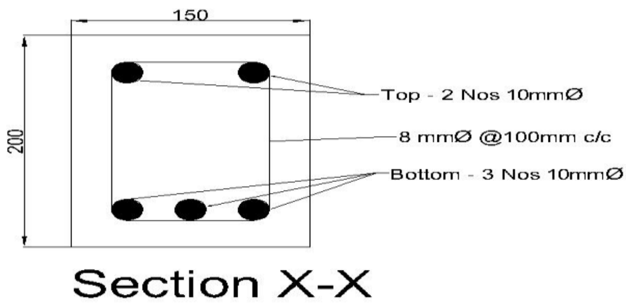


Fig. 4 - X-X Section details of beam

5. Result and Discussion

5.1 Assessment of Physical Property of the Binder

Table 7 contains the experimental results of the physical properties of the binder different parameters. These parameters are very important for determining the suitability of the binder. The experimental results of physical properties of the binder i.e., AAB are within an acceptable range of the relevant Indian standard Indian standard, [IS 12089:1987]

Table 7 - Physical properties of binder combination with different percentages of alkali

Physical Properties	GGBFS with5% alkali	GGBFS with 6% alkali	GGBFS with 7% alkali	GGBFS with 10% alkali
Specific gravity	2.70	2.73	2.79	2.89
Standard consistency (%)	32.5	32.5	33	34
Soundness (Le-Chatelier) (mm)	1.3	1.3	1.2	1
Initial Setting time (minutes)	80	72	65	58
Final setting time (minutes)	256	251	230	219

5.2 Compressive Strength of Binder

The activator solution is mixed with water for 10 minutes to achieve a homogenous solution. Then mortar sample of cube size 70.6 mm x 70.6 mm x 70.6 mm was prepared with binder: sand in ratio of 1:3. The cast samples were left in the mould for 24 hours, then removed and placed under water curing condition for 1, 3,7 and 28 days. Figure 5 shows the experimental results of compressive strength of the mortar cube with the binder i.e. AAB which are within an acceptable range of the relevant Indian standard, [IS: 12089:1987].

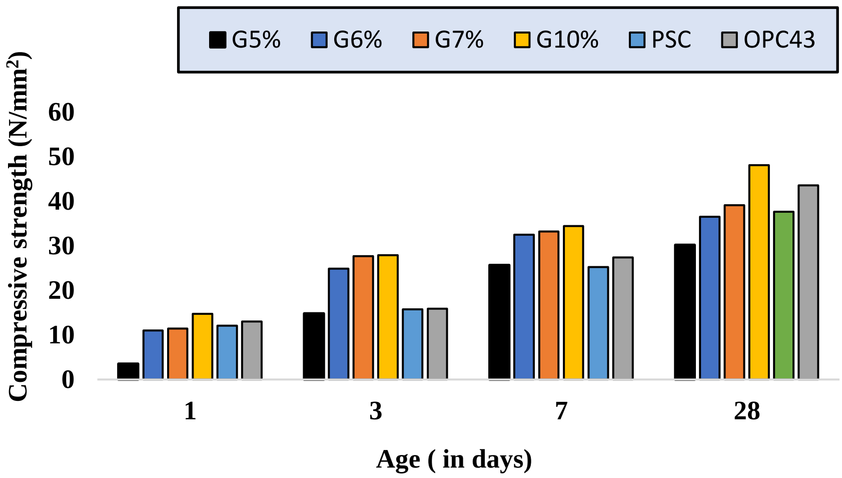


Fig. 5 - Compressive strength of mortar vs. days

5.3 Workability

The test results of the workability test all AAB concrete was found to be similar to that of OPC and PSC concrete as depicted in Figure 6. The workability of concrete with binders G5, G6, PSC and OPC 43 are fall in the same rage. The G7 and G10 show relatively higher workability when compared with the rest concrete mix. The increase in the workability may be due to increase of dose of the activator. Hence, the workability of the AAB concrete is proportional to dose of activator. The water-binder ratio is the same for all the mixes. In the earlier research work, the activators were prepared by either strong alkalis or silicates or by mixing both [Nguyen, 2019]. In the present research work, the activators are being used in powder form of the sodium and calcium for activation.

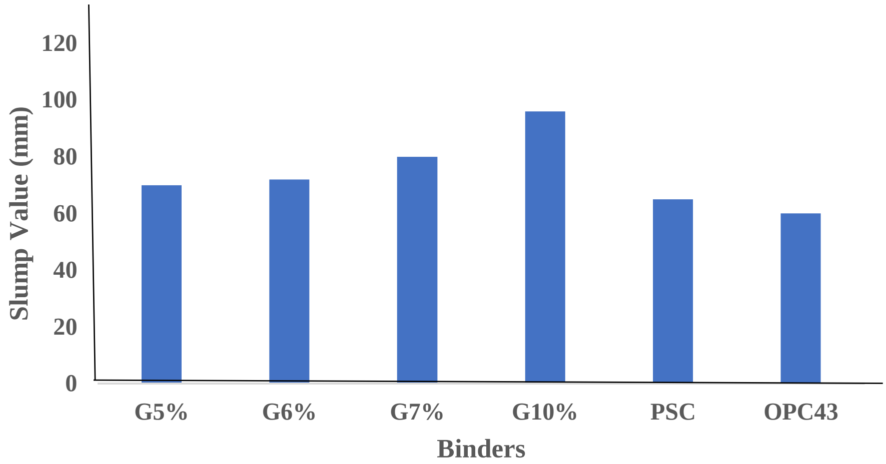


Fig. 6 - Workability of GGBFS, PSC and OPC at W/B 0.48

5.4 Mechanical Properties of Concrete

In order to understand the mechanical properties of developed concrete, three basic tests of strength have been conducted: (i) compressive strength, (ii) split tensile strength and (iii) flexural strength test. The specimens were cast as per the mix detail in Table 6. The samples are in the shape of cubes, cylinders and prisms. The tests were performed under saturated surface dry conditions. The samples were tested in different age of maturity i.e. 1, 3, 7, 28, 90,180 and 365 days.

5.4.1 Compressive Strength of Concrete

Figure 7(a) depicted the result of the compressive strength of activated binder concrete. The compressive strength of the AAB concrete is directly proportional to the dose of activator. Initially, the rate of gain of compressive strength of activated binder is higher and after 28 days of maturity, the rate of gain of compressive strength becomes stagnant. At 28 days of maturity, the G5 group concrete shows the lowest compressive strength whereas G10 group concrete shows the highest compressive among all type of the concrete. After 28 days of curing, the G5%, G6% and PSC concrete show compressive strength almost in the same range, whereas for G10% concrete, the development of compressive strength is greater than that of the compressive strength of all the concrete binder. The compressive strengths of the concrete with G10%, OPC 43, PSC, G7% G6%, and G5% are 44.72 N/mm^2, 43.46 N/mm^2, 38.08 N/mm^2, 37.75 N/mm^2 and 36.09N/mm^2 , respectively after 365 days.

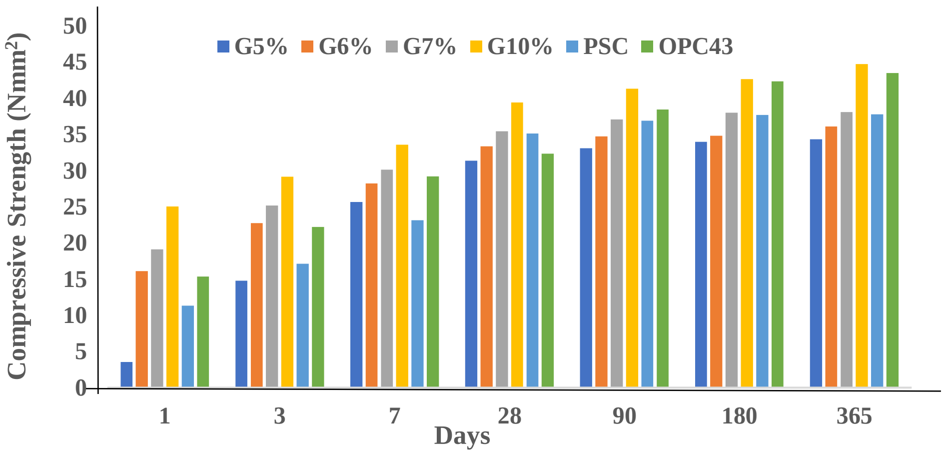


Fig. 7 (a) - Compressive strength of concrete vs. age

5.4.2 Split Tensile Strength

At the initial age of maturity, the split tensile strength of the alkali-activated binder concrete is higher as compared to the concrete with conventional cement i.e. OPC and PSC. At higher age of maturity, the strength development of the activated binder concrete is slightly lower as compared to the concrete with conventional cement i.e. OPC and PSC. Here, the concrete with OPC43 and PSC concrete is considered as the reference mix. At the age of 365 days of maturity, the split tensile strength of G5%, G6%, G7%, G10%, PSC, and OPC43 concrete are 6.1 N/mm^2, 6.34 N/mm^2, 6.4 N/mm^2, 6.71 N/mm^2,6.32 N/mm^2 and 6,56 N/mm^2 respectively. In figure 7 (b), it can be seen that the of rate of gain in split tensile strength of alkali activated concrete is faster at lower age of maturity as compared to higher age of maturity.

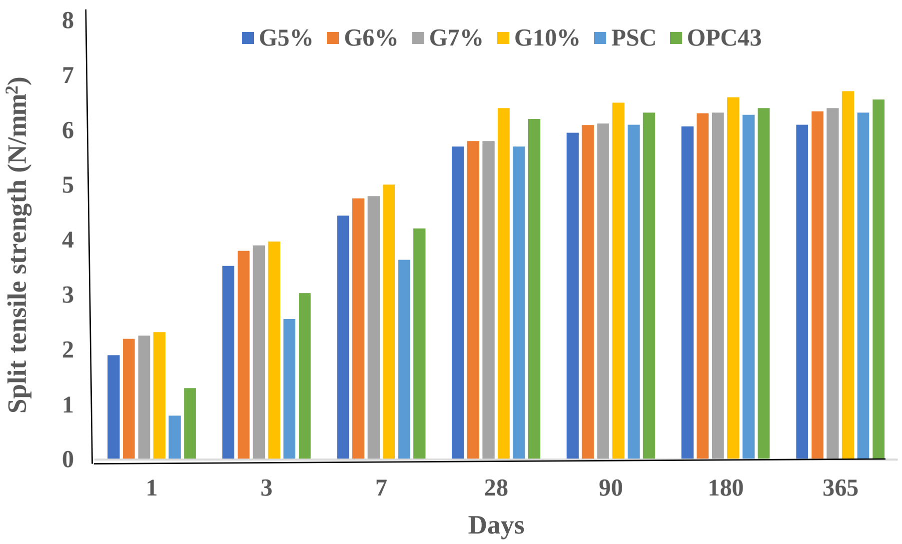


Fig. 7 (b) - Split tensile strength vs. age

5.4.3 Flexural Strength

Figure 7 (c) shows the development of flexural strength of AAB concrete with different percentages of alkali content G5%, G6%, G7%, G10% and traditional binder PSC and OPC 43. The difference in the flexural strength is due to the molarity of alkali in activated binders in which the AAB concrete with G10% has highest flexural strength among all. The flexural strength of AAB concrete with G5%, G6% and G7% increases rapidly up to 7 days of maturity. A considerable amount of increase in the flexural strength has been observed in AAB concrete irrespective of percentage of alkali activator content after 7 days of maturity and it becomes stagnant after 28 days of maturity.

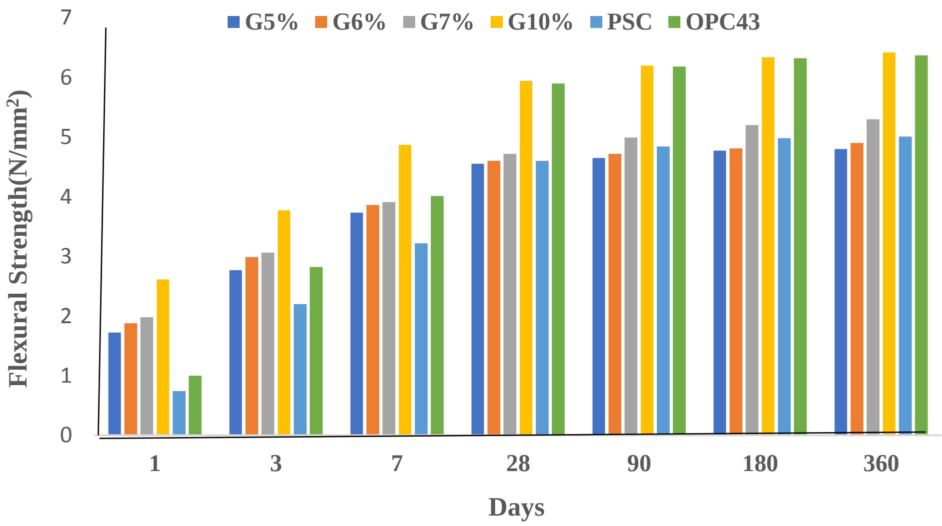


Fig. 7 (c) - Flexural strength vs. age

5.5 Flexural Behaviour of Reinforced Concrete Beam and Failure Modes

The failure of reinforced concrete (RC) beam was found to be in bending for the reinforced concrete beams with AAB concrete. Initially with gradual increase in the load, the cracks formation were started in the bending zone of the reinforced concrete beams, and with further load application, the beam deflection was increased and more numbers of cracks were appeared. The crack initially formed at the bottom of the beam and propagated toward the top of the beam sample.

5.5.1 Load Deflection Characteristics

The RC beams were tested in bending to evaluate ultimate strength in flexural. Initially, the beams were placed on the testing platform and the loading jacks were placed as per the requirement in Figure 3. The vertical displacement of the beam was measured with a linear variable differential transducer (LVDT) placed in the centre of the lower part of the beam sample. The applied load is servo controlled and the rate of deflection applied is 0.1 mm/min [Kalaivani, 2017]. After load application, the graph between flexural loading and deflection is linear as appears from Figure 8(a) and 8 (b), it increases with increase in the loading. The first crack appears at 60-63% of theoretical load for G5, G6, G7 and OPC reinforced beam. For PSC concrete, the first crack appears at 57.30% of the theoretical load whereas, for G10 the first crack appears at 73.62% of the theoretical load. With increase in the load further, several cracks were appeared in the bending zone as shown in Table 8. At the later stage, while loading more number of cracks were also appeared in the shear zone but it was not even propagated to half of the beam. While loading, the nonlinear behaviour was observed after exceeding the theoretical load. The cracks at ultimate flexural load were also noted on the specimens corresponding to 142.4%, 150.3%, 162.9% 181.5% 154.8% and 169.38% of the theoretical load for G5%, G6%, G7%, G10%, PSC and OPC concrete, respectively. At the end of testing, the RC beam was subjected to load above ultimate loading, more number of cracks were appeared in many places with increased width.

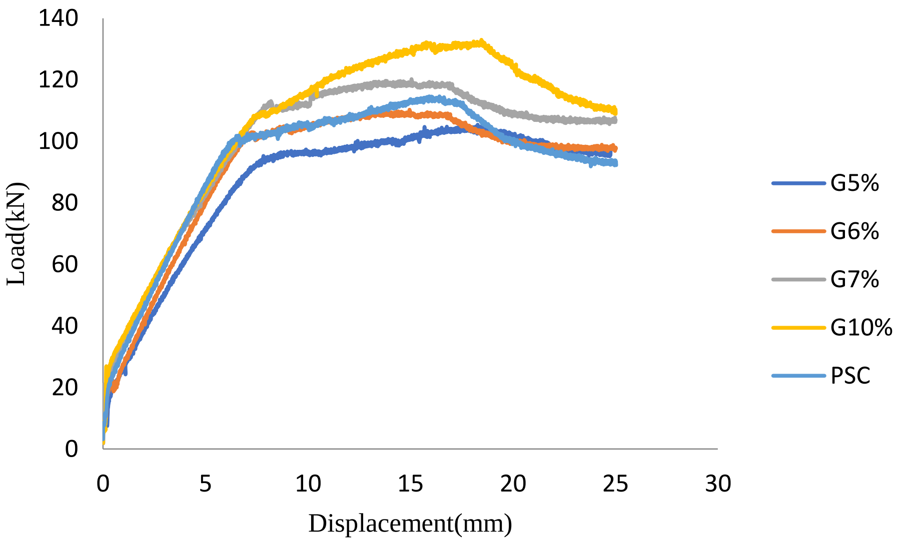


Fig. 8 (a) - Flexural strength of PSC vs. different concentration of alkali

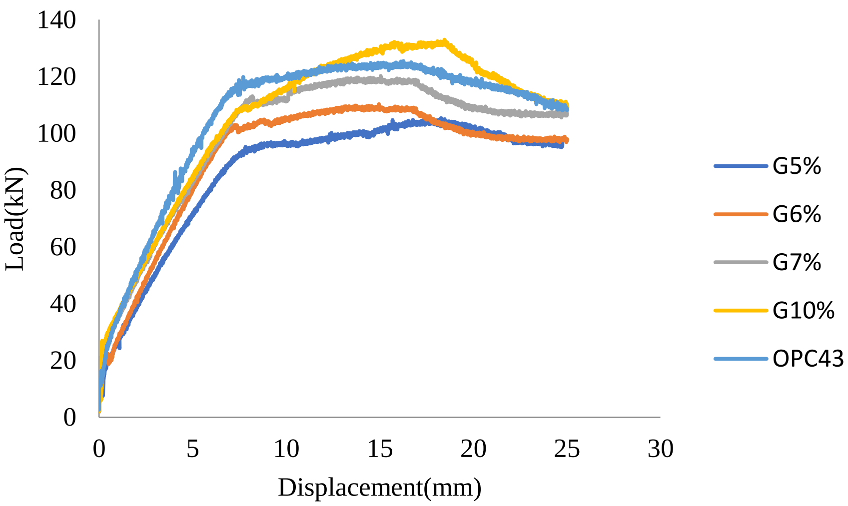
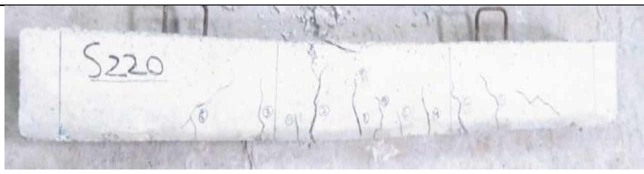
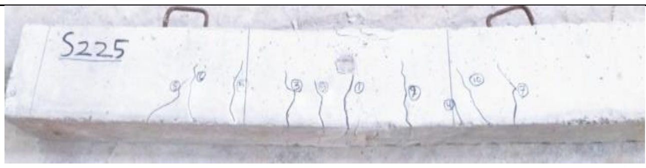


Fig. 8 (b) - Flexural strength of OPC vs. different concentration of alkali

Table 8 - Details of RC beam with AAB concrete

SL.No	Specimen	Designated activator	Designation of RC Beam
1.		G5%	S220
2.		G6%	S225
3.		G7%	S230
4.		G10%	S240
5.		-	PSC
6.		-	OPC43

The initial crack load that occurs on the beam is called the first crack load, and the maximum load bear by the beam is called the maximum bearing capacity of the beam. Figures 9 and 10 show the first flexural load and the maximum bearing capacity of the AAB concrete is given in Table 9. The first crack loads of samples G5%, G6%, G7%, G10%, PSC and OPC 43 are 44 kN, 46 kN,47 kN, 54 kN, 42 kN and 46 kN, respectively and the ultimate loads of samples G5%, G6%, G7%, G10%, PSC and OPC 43 are 104.57 kN, 110.27 kN and 119.61 kN, 131.94 kN, 114.52 kN and 124.70 kN, respectively. It is being observed that the first crack load and the ultimate load-carrying capacity are being increased with increase in percentage of alkali activator in AAB concrete.

Table 9 - Load carrying capacity of alkali activated reinforce concrete beam

Sl. No	Binder type	Experimental max. load (P_e) - kN	Theoretical max. load (P_t)- kN	P_e/P_t	Deflection at max. load(mm)
1.	G5%	104.44	73.34	1.42	16.52
2.	G6%	110.22		1.50	11.75
3.	G7%	119.46		1.62	14.40
4.	G10%	133.11		1.81	17.19
5.	PSC	113.50		1.55	17.18

6.	OPC43	124.22		1.69	16.75
* The beams were designed to fail in flexure and safe in shear					

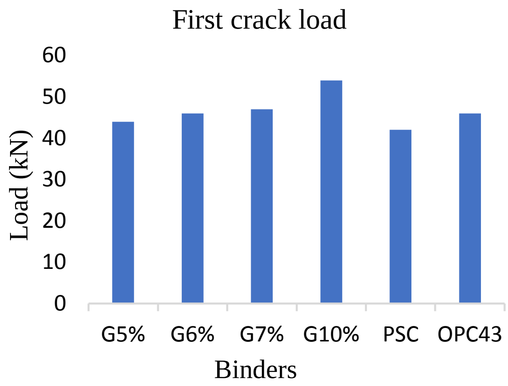


Fig. 9 - First crack load of AAB

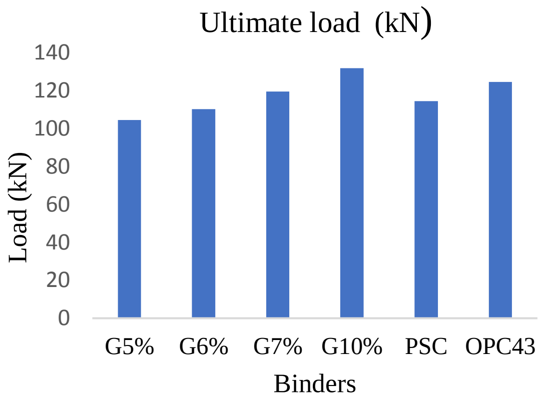


Fig. 10 - Ultimate load of AAB

6. Summary and Conclusion

In this experimental investigation, the following conclusions were drawn.

1. The physical properties of the alkali activated binders are found to be remain same irrespective of concentration of the alkali.
2. The development of compressive strength, split tensile strength and flexural strength of the AAB concrete with G5%, G6% and G7% alkali activator are equivalent to PSC concrete except the OPC concrete which shows higher value of the strength. G10% binder is higher than all binder.
3. The ultimate load carrying capacity of reinforced concrete beams with G5%, G6%, G7%, PSC and OPC-43 are in the same range whereas the RC beam with G10% exhibit higher value.
4. Finally, the alkali activated binder, i.e. AAB has a possible potential to replace PSC and OPC and it gives advantage over the conventional cementitious binder. AAB binder is totally green in nature as it is a waste material and it does not require any energy in manufacturing.

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