DOI: https://doi.org/10.14256/JCE.3830.2023

Građevinar 1/2025

Primljen / Received: 23.7.2023.
Ispravljen / Corrected: 15.1.2024.
Prihvaćen / Accepted: 25.2.2024.
Dostupno online / Available online: 10.2.2025.

Flexural behavior of sustainable high volume fly ash in (HVFA) reinforced concrete beam

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Research Paper

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Utilizing a high volume of fly ash as a replacement to cement in concrete is not widely practiced because of less strength gain in the earlier days. The fly ash at a replacement rate of 50 % was used in the C25/30 grade concrete to develop the sustainable HVFA concrete. The addition of 50 % of fly ash in the concrete reduces the heat increase and embodied energy with enhanced mechanical properties and structural behavior. The load carrying capacity of the beam was increased by 57 % at 7 days, along with 53 % reduction in ultimate deflection with the addition of only 2.5 % of accelerator.

Key words:

fly ash, sustainable concrete, high early strength, reduced CO_2 emission, flexural behavior

Prethodno priopćenje

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Ponašanje pri savijanju održive armiranobetonske grede s velikim udjelom letećeg pepela

Šira upotreba velikih količina letećeg pepela kao zamjene za cement u betonu nije uobičajena zbog manjeg povećanja razine čvrstoće u ranoj starosti. Leteći pepeo u stopi zamjene od 50 % korišten je u betonu kvalitete C25/30 za razvoj održivog betona s velikim udjelom letećeg pepela. Dodatak od 50 % letećeg pepela u betonu smanjuje povećanje topline hidratacije i ugrađenu energiju uz poboljšana mehanička svojstva i strukturno ponašanje. Nosivost grede povećana je za 57 % nakon sedam dana, uz smanjenje krajnjeg otklona od 53 % uz dodatak samo 2,5 % akceleratora.

Ključne riječi:

leteći pepeo, održivi beton, visoka rana čvrstoća, smanjena emisija CO_2, ponašanje pri savijanju

1. Introduction

With recent developments in civil engineering, concrete has become the most broadly utilized material in construction, which demands a high rate of cement production [1]. In present days, the cement industry consumes a large number of natural resources and emits a large amount of of greenhouse gases [2]. One billion tons of cement production causes atmosphere pollution through the emission of an equal amount of CO_2 [3]. This advances the use of materials like Ground Granulated Blast-furnace Slag (GGBS), fly ash, and otheras supplementary materials for cement, particularly in concrete production [4-7], which are commonly known as Supplementary Cementitious Materials (SCM). The environmental effects and financial expenses of the cement industries can be alleviated and somewhat compensated by the utilization of fly ash, GGBS, rice husk, silica fume, etc., as a supplementary material to cement [8, 9]. Recently, the development of sustainable concrete as a concept of saving energy, conservation of natural resources and protection of the environment has drawn wide attention. The usage of GGBS, fly ash and silica fume has made some contribution in the development of sustainable concrete. The presence of Al_2O_3 and SiO_2 in these materials possess pozzolanic properties when in reaction with Calcium Hydroxide (CH) during the hydration process and form additional Calcium Silicate Hydrate (CSH) and Calcium Aluminate Hydrate (CAH), which contributes to the formation of a denser matrix and offers better durability and strength [10]. Looking from a practical perspective, fly ash, GGBS and silica fume can be added to concrete at a rate of 20 - 30 %, 40 - 50 % and 5 - 10 % instead of cement [11]. A huge quantity of fly ash is generated every year worldwide [12, 13]. Only a small amount of fly ash utilized, that is around 20 - 30 %, and the rest is landfilled, which becomes a potential danger to ecological contamination [14, 15]. The fly ash is usually spherical in shape and its sizes range from 1 to 100 µm. The specific gravity and surface are in the range of 1.9 to 2.8 and 300 to 500 m^2/kg. Fly ash is classified based on limit content as class-C and class-F. Its main element is amorphous silica, which interacts with $Ca(OH)_2$ present in cement. It prompts the development of calcium silicates and contributes to the cement matrix strength. Since Portland Cement (PC) comprises about 65 % of lime and a portion of it remains free after the hydration, it is essential to bring a pozzolanic additive into the concrete for neutralizing the lime and thus enhancing the properties of concrete. The utilization of fly ash in the production of concrete decreases the cement cost and increases the resistance to corrosive aggressive conditions [16]. Lye et al. [17] demonstrated that the relative rate of carbonation of fly ash remains the same as that of OPC under accelerated and natural carbon dioxide exposure. Jee and Pradhan [18] revealed that the cement replaced with 20 % fly ash in the reinforcement concrete can enhance the performance of the beam against the corrosion of steel reinforcement. Recently, numerous examinations have been directed to utilize high amount of fly ash in the concrete as supplement to cement, because of its valuable effects on concrete properties, which is called High Volume Fly Ash (HVFA) Concrete. The earlier strength gain is mostly related to the w/c ratio. The low w/c in concrete acquires strength more quickly than the high w/c in concrete mix. This is because the cement grains are nearer to each other and a continuous system of gel is formed more quickly [19]. The HVFA concrete is not applicable for high-speed construction. The major detriment of HVFA is a sharp decrease in concrete strength, especially at earlier ages inferable from the slow reaction of fly ash containing a high quantity of CaO. It was reported that CaO has not reacted during the early ages under normal curing conditions [20]. At later ages, the HVFA concrete strength might equalize or surpass the conventional concrete strength dependent on the amount, fineness of FA, reaction rate of FA, w/c and curing conditions.

The earlier strength attainment is a significant issue in HVFA concrete. This restricts the utilization where high earlier strength is essential. To overcome this issue, a ternary blend of OPC, silica fume and fly ash was proposed by various researchers [21-24]. The silica improves the earlier strength attainment of the concrete by forming the secondary C-S-H gel at early stages because of quick pozzolanic reaction. Many studies have been performed on the determination of the properties of concrete with a replacement level of 20 to 30 % of OPC with fly ash and silica fume. Bouzoubaa et al. [25] reported that there was no significant improvement in the earlier strength gain of the concrete containing 8 % of silica fume with 40 % of fly ash. Hence, the use of fly ash with other SCM to attain earlier strength gain requires intensiveresearch. On the other hand, few studies [26-28] recommended that the addition of an accelerator can increase the earlier strength gain property of the concrete.

Kesharwani *e*t al. [29] concluded that cement replaced by fly ash is appropriate only for a low concrete grade like M20. It was concluded that cement replaced by 25 % of fly ash possesses only an impressive increase in strength. Ananyachandran and Vasugi [30] examined the early strength gain of the concrete made with 30 %-50 % of the fly ash mixed along with accelerator admixtures like $Ca(NO_3)_2$ in combinations with Tri-ethanolamine ($C_6H_{15}NO_3$). The mix contains 30 % of fly ash with 1 % of $Ca(NO_3)_2$ and 0.05 % of $C_6H_{15}NO_3$ which gives the maximum strength gain of 18.23 % and 54.29 % at 1 and 3 days. Salain et al. [31] examined the impact of the accelerator on the earlier strength gain of the concrete made with 10 % of class-F fly ash. The addition of 2.5 %, 5 %, 7.5 % and 10 % of accelerator into the fly ash concrete increases the compressive strength by 31.8 %, 31.1 %, 27.1 % and 24.1 %. Sounthararajan and Sivakumar [32] carried out a research on the high strength concrete mixed with 50 % of fly ash along with metallic fibers, and obtained high strength of about 50.7 MPa at only 7 days of curing. Lee et al. [33] used CSA to enhance the earlier strength gain and also investigated impacts of accelerators to exhibit the appropriateness of the concrete mixture. As noticed, the optimum amount of CSA for the attainment of earlier strength was 17 % of the binder with 1.9 ratio of CaO/SO_3 and a 1.25 ratio of SO_3/Al_2O_3. It was clear that CSA mixed with Na_2SO_4 promotes the earlier strength gain. Sharma et al. [34] focused primarily on accelerating admixtures that are apportioned into the concrete mix at a different rate to acquire a highly effective mix. The mix made with a type C accelerator (Plastol Ultra 209) gained 4 % to 5 % higher strength than the mix with type B (Sika Viscocrete HDP20) and D accelerators (Masterset AC 100).

Murtiadi et al. [35] investigated the effect of chemical accelerator and normal curing on normal concrete and high strength. Based on the the outcomes, they concluded that the chemical accelerator and steam curing highly contribute to attaining the earlier strength. Naqash et al. [36] used sodium nitrate accelerating admixture at a rate of 1 %, 1.5 %, 2 %, 2.5 % and 3 % ofcement weight. The optimum rate of accelerator that could be used without affecting the concrete properties was examined. The outcomes concluded admissibility that utilizing sodium nitrate as accelerating admixture up to 2.5 % enhances the compressive, flexural and tensile strength at 3 and 7 days of curing. Suto and Niwase [37] conducted research to improve the earlier strength gain by utilizing a mix of various chemical admixtures. The chemical admixtures used are Master Ease (ME) which is used as air-entraining admixture and Master X Seed (MXS) which is used as an accelerating admixture. The strength of LPC-ME-MXS concrete was found to be higher than OPC-ME at 3 days of curing. From the literature reviews, it was observed that significant contribution has been made to the utilization of fly as a supplementary, as well as utilization of accelerator for earlier strength attainment of the fly ash concrete. The majority of the study concluded that utilization of fly ash up to 30 % was optimum. Beyond the addition of 30 % fly ash adversely affects the properties of concrete. Hashmi et al. [38] reported that the concrete made with 40 % of fly ash can achieve only 78 % of the cement achieved by the OPC concrete at 28 days. Sounthararajan and Sivakumar [32] found that the earlier strength of the concrete made with 50 % of fly was less when compared to the concrete made with 25 % of fly ash. The use of a high volume of fly ash leads to a sustainable and better future. Because of urbanization and huge population growth, the natural resources are depleting much faster, which presents a number of challenges to researchers, developers and industrialists. In construction, the demand for building materials like concrete is increasing exponentially. So, higher use of fly ash in construction projects will not only solve the fly ash disposal problems, but also help in the exhausted consumption of natural resources, thus prompting sustainable development. Hence, this study uses the high volume of fly ash (50 %) for the production of concrete with better earlier strength gaining properties and analyses the impact on the appropriate utilization of accelerator admixture for earlier strength gain. To the best of our knowledge, this study is the first attempt to investigate the impact of accelerator admixture on HVFA concrete beam.

2. Materials

This research work investigates the impact of accelerator admixtures on the mechanical properties and flexural performance of High Volume Fly Ash (HVFA) concrete. An extraordinary consideration was given to designing a concrete mixture for accomplishing the high strength utilizing conceptual proportioning strategy by considering the binder ratio to total aggregate, and fine to coarse aggregate ratio. Comprehensive experimental tests comprising slump cone, and compressive and tensile strength have been led to examine the performance of high volume fly ash concrete.

Cement: The cement utilized was Coromandel King OPC 53 grade. The loss of ignition was 0.98, specific gravity was 3.15 and the chemical composition of cement is given in Table 1.

Table 1. Chemical composition of cement

Composition	Amount [%]
SiO_2	20.81
Al_2O_3	4.79
Fe2O3	3.2
CaO	63.9
MgO	2.61
SO_3	1.39
Na_2O	0.18
K_2O	0.79
Cl^-	0.002

Fine aggregates: The locally available river sand which passes through sieves of 4.75 mm, conforming to grading zone-II of IS: 383–1970 [39], was utilized with a fineness modulus of 2.57, a specific gravity of 2.71 and water absorption of 0.67 % tested under standard conditions.

Coarse aggregates: The well-graded angular granite stone with a maximum size of 20mm, conforming to IS: 383–1970 [39] was used. The specific gravity was 2.7, the fineness modulus was 7.2 and water absorption was 0.62 %.

Fly ash: A Class-F fly ash obtained from the Ennore thermal power plant was utilized in the current examination. The loss of ignition was 1.9 %, specific gravity was 2.2, moisture content was 0.73 % and their chemical composition is given in Table 2.

Table 2. Chemical composition of fly ash

Composition	Amount [%]
SiO_2	59.3
Al_2O_3	34.6
Fe2O3	5.87
CaO	1.02
MgO	0.38
SO_3	0.1
Na_2O	1.28
K_2O	0.01
Cl^-	0.49

Chemical admixture: A CERAPLAST-ACL which is a calcium nitrate-based accelerator having a specific gravity of 1.82 and solid content of 25 % used as an admixture to accelerate the pozzolanic reaction in the concrete.

Table 3. Mix proportion

Accelerator [%]	ID	Cement [kg/m³]	Fla ash [kg/m³]	Fine aggregate [kg/m³]	Coarse aggregate [kg/m³]	Accelerator [kg/m³]	Water [kg/m³]
0	CC	270.87	270.87	601	924..59	0	197
0.5 %	A0.5 %	270.87	270.87	601	924.59	2..7	197
1 %	A1 %	270.87	270.87	601	924.59	5.14	197
1.5 %	A1.5 %	270.87	270.87	601	924.59	8.124	197
2 %	A2 %	270.87	270.87	601	924.59	10.832	197
2.5 %	A2.5 %	270.87	270.87	601	924.59	13.54	197
3 %	A3 %	270.87	270.87	601	924.59	16.248	197
3.5 %	A3.5 %	270.87	270.87	601	924.59	18.956	197
4 %	A4 %	270.87	270.87	601	924.59	21.664	197
4.5 %	A4.5 %	270.87	270.87	601	924.59	24.372	197
5 %	A5 %	270.87	270.87	601	924.59	27.08	197

Table 4. Embodied energy (EE) of fly ash concrete and OPC concrete

Ingredients	OPC concrete		Fly ash concrete		Accelerator added fly ash concrete	
	Quantities [kg/m³]	**EE** [MJ/m³]	**Quantities** [kg/m³]	**EE** [MJ/m³]	**Quantities** [kg/m³]	**EE** [MJ/m³]
Cement	541.74	2599.26	270.87	1299.63	270.87	1299.63
Fly ash	0	0	270.87	27.08	270.87	27.08
Fine aggregate	601	52.287	601	52.287	601	52.287
Coarse aggregate	924.59	76.74	924.59	76.74	924.59	76.74
Water	197	39.4	197	39.4	197	39.4
Accelerator	0	0	0	0	27.08	310.71
Total		**2767.68**		**1495.13**		**1805.84**

3. Experimentation

Ten different types of C25/30 grade concrete were prepared with the addition of 0 to 5 % of the accelerator at an interval of 0.5 % to the weight of cementitious material,proportioned as per IS:10262-2009 [40]. The concrete was tested for the slump flow and mechanical properties like compressive strength, split tensile strength, flexural strength and also flexural behavior of the beam. The mix does not contain the accelerator (0 %) is considered as Control Concrete (CC). Table 3 shows the mix proportion of concrete with various percentages of accelerators. Initially, coarse aggregate and fine aggregate were fed into the mixer and mixed for 2 minutes, Then, the required amount of cement was introduced into the mixture and mixed for 2 minutes in the dry condition. On the other side, the appropriate amount (0 %, 0.5 %, 1 %, 1.5 %, 2 %, 2.5 %, 3 %, 3.5 %, 4 %, 4.5 % and 5 %) of the accelerator was added with the required amount of water. The water and accelerator mix were added to the mixer containing cement, coarse and fine aggregate and mixed for a period of 4 min. The prepared fresh concrete was tested for its workability properties using a slump cone and the slump value was measured. A 100 mm cube specimen was cast for testing the compressive strength as per IS: 516-1959 [41]. A cylinder specimen of size 100 mm diameter × 200 mm height was cast for testing split tensile strength as per IS:5816-1959 [42]. A prism specimen of size 100 x 100 x 500 mm was cast for testing the flexural strength or modulus of rupture as per ASTM C293/C293M [43]. All the specimen was demolded after 24 hours of moist curing and then introduced into the water tank for curing. After 7 days, 14 days and 28 days of curing, the specimens were tested for their properties.

3.1. Embodied energy of fly ash concrete

The energy requirement is high in construction industry. The energy used for manufacturing, transportation, actual utilization in construction and after construction is called embodied energy. Embodied energy (EE) is the sum of all energy needed to produce any good and services, considered as if that energy was incorporated or embodied in the product itself. The embodied energy concept was helpful in the determination of the effectiveness of energy-producing or energy-saving devices, or the real replacement cost of the building, because the energy inputs involve greenhouse gas emissions. One crucial reason for estimating this amount is to compare the amount of energy produced or saved by the product in question to the amount of energy consumed in producing it. It also helps in finding the total amount of energy necessary for an entire life-cycle of the products. The energy in construction might be viewed from two various perspectives. Firstly, the energy goes into the construction of the building utilizing various

Table 5. Details of beam specimen

Specimen ID	Accelerator [%]	$\rho = A_{st}/bd$ [%]	Area of tensile steel (A_{st}) [mm^2]
CC	0	0.75	226.19
A2.5 %	2.5		

materials like cement, steel, aggregates, etc. Secondly, the energy that is used to create a comfortable environment within the building during its entire lifetime [44]. A number ofresearchers have studied the embodied energy in construction materials over several years in the relationship between building materials, the construction process, and their environmental effects. Recently, these embodied energy subjects have become of greater importance due to the increase in the energy efficiency of the building [45]. The embodied energy of the OPC was found to be 54 % higher than the fly ash concrete. Hence, the replacement of cement with 50 % of fly ash in the concrete will reduce the embodied energy by 54 %. Accordingly, the replacement of cement by 50 % of fly ash with the addition of an accelerator in the concrete reduces the embodied energy by 34 % as presented in Table 4.

3.2. Determination of cCompressive strength of concrete

The compressive strength test was performed as per the IS: 516-1959 [41] using the cube specimen of size 150 x 150 x 150 mm. The test specimen was placed in the UTM and loaded up to the failure of the specimen. The compressive strength was determined using the Eq. (1),

$$\sigma = \frac{F}{A} \tag{1}$$

σ is the compressive strength of the concrete [MPa], *F* is the failure load [N], *A* is the surface area of the concrete [mm].

3.3. Determination of split tensile strength of concrete

The split tensile test was performed as per the IS: 5816-1959 [42] using the cylinder specimen of size 150 x 300 mm. The test specimen was longitudinally placed in the UTM and loaded up to the failure that occurred along the vertical diameter of the specimen. The tensile strength of specimen was determined using Eq. (2),

$$\sigma = \frac{2P}{\pi DL} \tag{2}$$

σ is the split tensile strength of the concrete [MPa], *P* is the failure load [N], *D* is the diameter of the specimen [mm], *L* is the height of the specimen [mm].

3.4. Determination of flexural strength of concrete

The Flexural strength was determined on the prism specimen of size 500 x100 x100 mm as per the IS 516-1959 [41] specifications. The modulus of rupture of the specimen was determined using the Eq. (3),

$$\sigma = \frac{FL}{bd^2} \tag{3}$$

σ is the modulus of rupture of specimen [MPa], *F* is the failure load [N], *L* is the length of specimen [mm], *b* is the width of specimen [mm], *d* is the depth of specimen [mm].

3.5. Determination of flexural behavior of the beam

The primary objective was to investigate the flexural the HVFC (A2.5 %) with addition of accelerator subjected to flexural loads under various parameters including load-carrying capacity, moment vs. deflection, ductility, cracking, stress-strain, and compared with OPC (CC) beam.

3.5.1. Design of the beam

A beam of size 150 x 230 x 3000 mm was designed as per IS:456-2000 [48] standards and used to determine the flexural behavior. All of the beams were designed as single reinforced beams and have 2 no's of 12 mm diameter bars in the tension zone and 2 nos of 10 mm diameter bars as hanger bars. A 25 mm concrete cover block was added to the beam. In order to achieve pure flexural failure in the center of the beam, the beam specimen was designed to resist the shear failure when the longitudinal tensile reinforcement yielded. For this reason, the two-legged stirrups with an 8 mm diameter were positioned in the beam at 150 mm spacing. Figure 1 shows the cross-sectional view of the beam specimen. Table 5 provides a detailed description about the reinforcement details of the beam specimen.

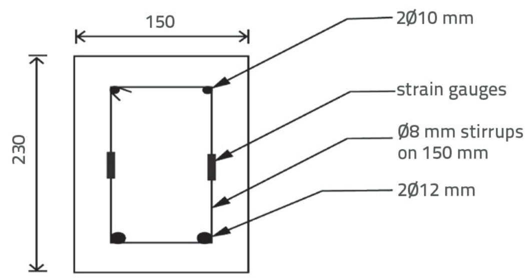

Figure 1. Cross-section of the beam

3.5.2. Casting of the beam

The mold was made with steel plate welded as per designed dimension of the beam. Using glue, the TML-10MM strain gauge with a resistance of 120 Ohms was pasted to the mid-span of the tension bar. Before pasting the strain gauge, the surface of the tension bar needs to be ground smoothly and scrubbed with fine

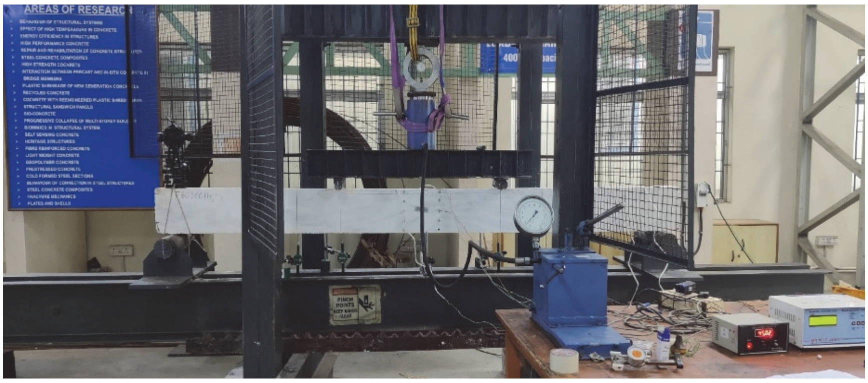

Figure 2. Test setup

salt paper. On a watertight platform, the concrete was mixed, and it was poured into the beam mold. The cement, fine aggregate, was initially weighted and mixed, and then the coarse aggregate is added to it and mixed. The accelerator mixed with water was added to that mixture. The specimen was demolded and allowed to cure for 7 days using gunny bags after undergoing moist curing for 24 hours.

3.5.3 Testing of the beam

The beam specimen was completely white-washed before the testing, and the center lines, neutral axis, and location for pasting the strain gauge were all precisely indicated. At a distance of d/2 from the front face of the beam, the strain gauge was fixed to measure the compressive strain. The half-bridge approach was used to connect the strain gauge's lead wires to a 10-channel strain bridge and data logger. To measure the deflections, a linear variable displacement transducer (LVDT) was positioned at the mid-span. The beam specimen after the 7 days of curing was tested for flexure under two-point loading using a loading frame of 1000kN capacity as shown in Figure 2. The beam specimen was first loaded under four-point loading in increments of 1 N after ensuring the safety of personnel, equipment and instruments. A handheld microscope with an optical magnification of 40 and a sensitivity of 0.01 mm was used to assess the width of the crack.

4. Results and discussions

4.1. Effect of accelerator on the heat of cement hydration

The exothermic temperature curves help to monitor the hydration process of the cement. A common method to study the reactivity of cementitious materials is by utilizing an isothermal calorimeter. Since hydration of cement is an exothermic reaction,, hence measuring the amount of heat liberated by these materials during hydration shows the amount of materials that have reacted. The typical cumulative heat of CC and HVFC concrete is presented in Figure 3, plotted as a component of time. It was observed that in the CC mix the induction period is as long as 3 hours, when the 1 % of accelerator is added into the mix, the induction period is reduced to 2 hours. With the concrete mix 2 % of accelerator the induction period is reduced to 1 hour. There was no induction period found for the 2.5 % accelerator mix, the temperature immediately begins to increase after the beginning of measurement, i.e., about 10 minutes after mixing the paste. The retardation of the initial hydration reaction of cement was observed for the CC mix because of dilution and interaction with fly ash particles [46]. It has been demonstrated that the increasing fly ash content results in decreased hydration reaction and delayed setting time at early ages. This trend was observed for the CC mix [47]. The addition of an accelerator accelerates the hydration reaction and decreases the setting time. This trend was observed for the A0.5 %- A5 % mix.

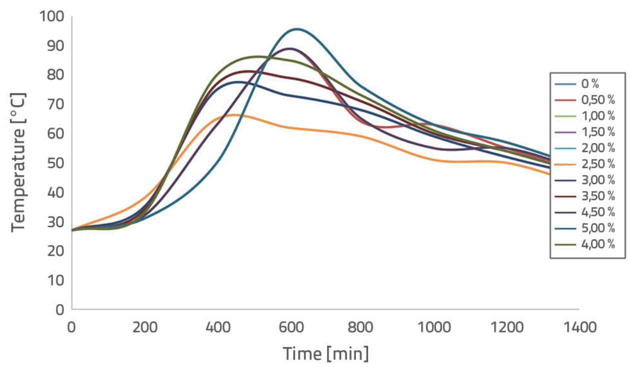

Figure 3. Heat of hydration

From Figure 3, it was observed that the addition of an accelerator decreases the maximum temperature. The CC mix reaches the maximum temperature of 95 °C. It was found that with a higher dose of accelerator (2.5 %), the temperature of the concrete mix decreasesduring the hydration process. This demonstrates that the hydration begins immediately, when there is more amount of the accelerator . The higher the dose of an accelerator, the shorter the time to reach the maximum temperature. With the addition of 0.5 %, 1 %, 1.5 %, 2 %, 2.5 %, 3 %, 3.5 %, 4 %, 4.5 % and 5 % of accelerator to HVFA, the hydration temperature drops to 89 °C, 85 °C, 79 °C, 73 °C, 62 °C, 73 °C, 79 °C, 85 °C, 89 °C and 95 °C. The higher temperature is worsening various types of disasters: storms, floods, drought, etc., and seriously threatens the environment. The reduced temperature will support sustainable development and enhance the environment.

4.2. Effect of the accelerator on setting time of cement

Table 6 presents the initial and final setting time of the HVFA concrete with the addition of accelerator admixtures. As the amount of accelerator used in the HVFA mix increases, the initial and final setting time of the concrete mix decreases. This is due to the calcium cation concentration in the accelerator which boosts the low calcium content in the fly ash, thus improving the strength-gaining effect. The Ca^{2+} dominates the setting, while NO_3 might have an impact also, contingent upon the type of cement.

Table 6. Initial and final setting time

Mixture	Initial setting [min]	Final setting [min]
CC	330	500
A0.5 %	285	470
A1 %	245	420
A1.5 %	190	380
A2 %	165	290
A2.5 %	145	210
A3 %	140	190
A3.5 %	135	180
A4 %	135	170
A4.5 %	130	150
A5 %	125	140

The addition of an accelerator to HVFA lessens the induction period, raises the initial temperature and accelerates the maximum temperature time; lessens the maximum hydration temperature.

4.3. Effect of the accelerator on workability of concrete

The slump value of various concrete mixtures with various % of accelerator is presented in Figure 4. The desired slump value of 75 to 100 mm was accomplished for control mixtures with the utilization of the fly ash. Also, the addition of an accelerator possesses some gaining of the slump value of around 4 %.

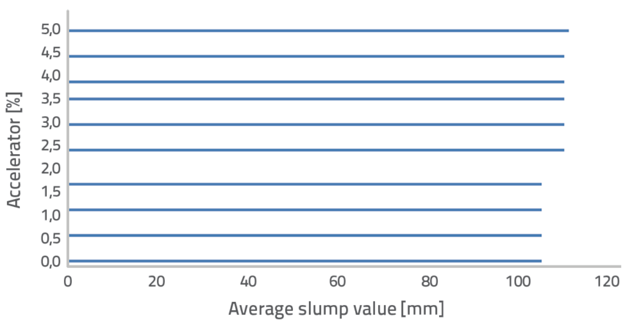

Figure 4. Variation of Slump Values with various % of accelerator

4.4. Effect of the accelerator on compressive strength of concrete

Figure 5 presents the compressive strength of the fly ash concrete with various percentages of accelerator admixtures. The addition of an accelerator strongly increased the compressive strength, particularly at an early age. The result is supported by Neville and Brooks [49], meaning that the addition of an admixture can boost the lime content of volcanic ash. The amount of strength gain capacity of the various mixes at 7 days is graphically presented in Figure 6. The addition of accelerator of 0.5 %, 1 %, 1.5 %, 2 %, 2.5 %, 3 %, 3.5 %, 4 %, 4.5 % and 5 % to the HVFA concrete attains 49.9 %, 52.8 %, 59.86 %, 64.73 %, 68.3 %, 66.1 %, 65.09 %, 48.89 %, 25.6 % and 23.2 % of its target strength with a curing period of only 7 days. The C_2S and C_3S play a more significant part in the development of the strength of cement paste than the other hydration products like C_2S C_3S, C_3A and C_4AF [50, 51]. The C_2S helps in the development of strength at later ages, whereas C_3S helps in the development of strength at earlier ages. The presence of calcium nitrate in the accelerator provides calcium ions which advances the hydration process and promote the formation of hydration products. With the accelerated hydration of C_3S and C_2S on Portland cement producing C-S-H and $Ca(OH)_2$, the pozzolanic reaction that occurred between alumina and silica reactive of fly ash and $Ca(OH)_2$ was also quicker to produce additional binder compound, C-A-H and C-S-H, which contribute to rising in compressive strength. This was ascribed to the abundant availability of free water during the early hydration process which facilitates the ionization of mineral Portland cement and fly ash. The hydration process turns out to be quicker, as well as the process of hardening with the concrete strength development. The compressive strength of the accelerator added HVFA concrete was found to be 4.6 %-8.8 % higher than the control concrete at 28 days. Sharma et al. [34] achieved a 17 % higher strength of concrete with the addition of 5 % accelerator admixture at 7 days. On comparing the achieved compressive strength results with results observed from the literature [32, 34, 44], it was concluded that utilization of higher volume fly ash in the concrete with an appropriate amount of accelerator, the maximum improvement in compressive strength was achieved, thus it prompts the sustainable construction practices with less impact on environment, energy and decreased CO_2 emissions. It was observed that the addition of an accelerator above 2.5 % shows a decrease instrength, which was associated with the presence of water in the accelerator. The high quantity of accelerator will have more amount of water, which tends to decrease the strength.

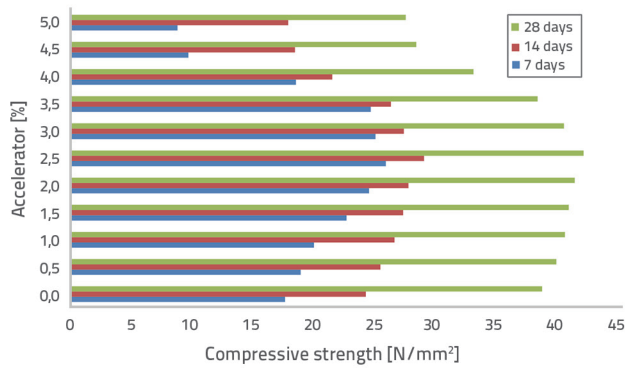

Figure 5. Variation of compressive strength with various % of accelerator

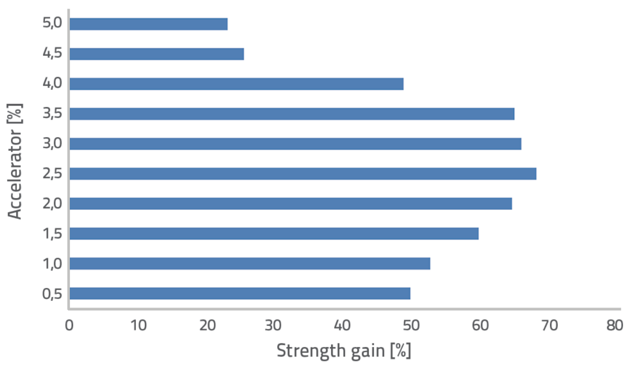

Figure 6. Strength gain of mix with various % of accelerator

4.5. Effect of the accelerator on split tensile strength of concrete

The cracking at earlier ages may occur because of volume changes due to thermal contraction and shrinkage. The effect of thermal and shrinkage effect induces tensile stresses in the concrete. If these stresses are higher than the tensile strength of the concrete, which is to some degree low at early ages, it can develop cracks in the concrete. Thus, it is essential to assess the tensile strength of the concrete at which the concrete may crack. The cylindrical specimen was tested as per IS: 5816-1959 [42], to determine the tensile strength of the concrete at 7 and 28 days. From the results, it was observed that the concrete made with accelerator admixture achieved higher strength at earlier ages. The tensile strength of the accelerator added in HVFA concrete was found to be 8.39 %-32 % and 7.2 %-155 % higher than the control concrete at 7 and 28 ages. Sounthararajan and Sivakumar [32] achieved the maximum split tensile strength of 3.58N/mm^2 for 25 % fly ash and 1.5 % steel fibers with 1 % of accelerator. In this study, a maximum split tensile strength of 3.89N/mm^2 was achieved with the utilization of a higher amount of fly ash of 50 % with 2.5 % of accelerator. This demonstrates that the utilization of a high volume of fly ash in the concrete does not affect the strength-gaining effect with the utilization of a high amount of accelerator. However, the proper proportion of accelerator is essential, as it was found that addition of the accelerator beyond 2.5 % shows decreasing in the tensile strength of the concrete as obtained for the compressive strength, as presented in Figure 7.

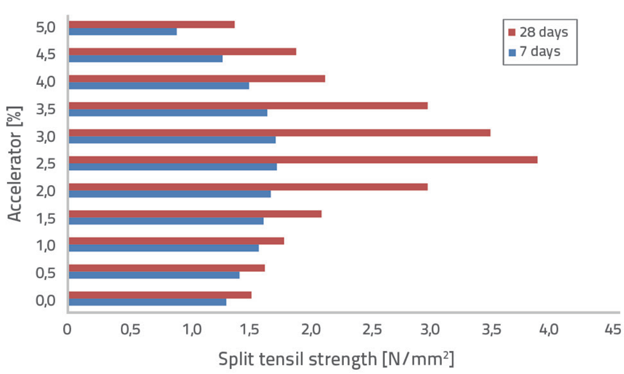

Figure 7. Variation of Split tensile strength with various % of accelerator

4.6. Effect of Accelerator on flexural strength of concrete

Flexural strength is one of the significant mechanical properties to consider in the study of HVFA, particularly for the fabrication of beams and slabs. Generally, the flexural strength increases with the age of curing and decreases with an increase in the fly ash content. Sounthararajan and Sivakumar [52] reported that with adequately low w/c, the HVFA concrete mix can achieve flexural strength based on its target compressive strength at 28 days. Accordingly, with a low w/c of 0.36, the flexural strength based on its target compressive strength at 28 days was achieved. The effect of the accelerator on the flexural strength of HVFA is presented in Figure 8. The flexural strength of HVFA concrete with accelerator was 2.3 %-21.01 % and 0.2 % to 4.34 % higher than the control concrete at 7 and 28 days. The increment of flexural strength was found to be decreased by increasing the accelerator content beyond 2.5 %. The HVFA concrete mix with 2.5 % accelerator possesses the highest accelerating effect, thus improving the flexural strength by 21.01 % at earlier ages (7 days). It was observed that the addition of the accelerator admixture improves the strength-gaining property of the fly ash concrete at earlier and later ages. However, the strength-gaining effect of the HVFA concrete with the accelerator was found to be higher at earlier ages (7 days). The test results demonstrate that the flexural strength particularly at earlier ages of the HVFA concrete was significantly improved because of the excellent excitation of the accelerator admixture on the pozzolanic reaction of the fly ash. This is vital for concrete, where the number of technical issues like high heat of hydration, high autogenous shrinkage and high brittleness will be solved by the large reduction of cement content.

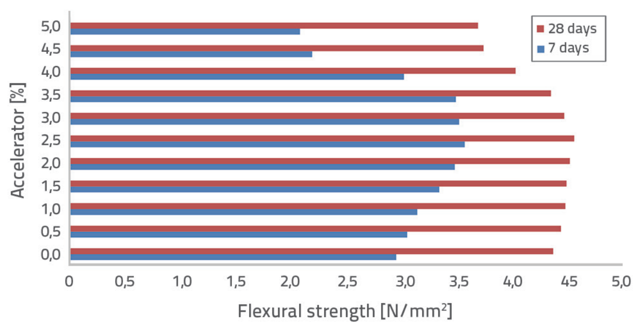

Figure 8. Variation of Flexural strength with various % of accelerator

4.7. Effect of accelerator on flexural behavior of the RC beam

The various results such as load-carrying capacity, moment vs. deflection, ductility, cracking, stress-strain of the beam tested under the flexural loading is presented in Table 7.

Table 7. Results on flexural behavior of the beam

Beam	First crack load [kN]	Ultimate load [kN]	Ultimate moment [kNm]	Ultimate deflection [mm]
CC	20	35	34.3	0.66
A2.5 %	35	55	53.9	0.31

Table 8. Experimental and Theoretical moment carrying capacity of beam

Beam ID	Experimental moment [kNm]	Theoretical moment [kNm]	
		EC2	BS-8110
CC	34.3	39.65	46.30
A2.5 %	53.9	43.14	50.03

4.7.1. Load and moment carrying capacity of the beam

It was discovered that the load bearing capacity of RC beams without fly ash (CC) is lower than the load bearing capacity of RC beams with fly ash (A2.5 %) which contains 270.87 kg/m^3 of cement, 270.87 kg/m^3 of fly ash, 601 kg/m^3 of fine aggregate, 924.59 kg/m^3 of coarse aggregate, 197 kg/m^3 of water along with 13.54 kg/m^3 of accelerator admixtures. The ultimate load-carrying capacity of the CC beam was 57 % less than the A2.5 % beam at 7 days. This demonstrates that the load-carrying capacity of the high-volume fly ash can be improved by the addition of an accelerator in earlier days. In general, the fly ash concrete possesses less strength in earlier days due to the slow pozzolanic reaction of the fly ash than the CC. Thangaraj and Thenmozhi [53] examined the flexural behavior of the OPC and HVFA beam made with 50 to 60 % class-f fly ash and reported that the load carrying capacity of the HVFA beam was 25 % less than the OPC beam. Hashmi et al. [54] reported that the load carrying capacity of the beam was decreased by 25 %, 46 % and 60 % with replacement of cement by 20 %, 40 % and 60 % of fly ash. However, in this study, the ultimate load-carrying capacity of the fly ash concrete was higher than CC at earlier days. This outcome shows that the utilization of an accelerator advances the hydration process of reactive hauyne minerals, thus initial production of ettringite also increased. Specifically, the Na_2SO_4 and $Al_2(SO_4)_3$ sulfate accelerators were effective for increasing the strength due to their quicker ionization rate and also initially eluted SO_4^{2-} ions are beneficial for the nucleation of ettringite hydrate [33]. The outcome of this study was supported by many literatures [55-57]. Soman and Sobha [55] achieved the 25.9 % improvement in load carrying capacity of the beam with replacement of fly ash by 50 %. Raj and Rao [56] achieved the 40 % improvement in load carrying capacity of the beam with replacement of fly ash by 30 % with maximum deflection of 9.93mm. Madan et al. [57] achieved the 53 % improvement in load carrying capacity of the slab with replacement of fly ash by 60 % with utilization of 3 layers of GFRP sheets. On comparing the obtained results with existing literatures [55-57], the obtained outcomes were found to better. Soman and Sobha [55] increased the load carrying capacity of the beam by only 25.9 % with replacement of fly ash by 50 %; Raj and Rao [56] increased the load carrying capacity of the beam by only 40 % with replacement of fly ash by 30 %; Madan et al. [57] increased the load carrying capacity of the beam by 53 % with replacement of fly ash by 60 % with utilization of 3 layers of GFRP sheets at 28 days. However, in this study, the load carrying capacity of the beam was increased by 57 % with replacement of cement by 50 % fly ash along with addition of only 2.5 % of accelerator at 7 days. The CC beam exhibits less load-carrying capacity than the A2.5 %, which might be due to the low compressive strength [58]. The ultimate moment capacity of the A2.5 % beam was found to be 57 % higher than the CC beam.

The European Code of Practice (EC2) [59] and the British Standard Code of Practice (BS 8110) [60] were used to calculate the theoretical ultimate moment of the beam. The ultimate moment of the beam was calculated by European Code of Practice (EC2) [59] using Eq (4);

$$M_u = 0{,}167 f_{ck} bd^2 \tag{4}$$

The ultimate moment of the beam was calculated by British Standard code of practice (BS 8110) [60] using Eq (5);

$$M_u = 0{,}156 f_{cu} bd^2 \tag{5}$$

where b is the width of beam; d is the effective depth of column; f_{ck} is the compressive strength of cylinder; f_{cu} is the compressive strength of cube.

The theoretically obtained moment carrying capacity of beam using EC2 and BS 8110 was compared with the experimentally determined moment carrying capacity of beam as presented in Table 8. It was observed that BS-8110 accurately determines the moment carrying capacity of beam with average variation of 7.17 to 34.9 %.

4.7.2. Load vs. deflection

The load vs. deflection of the CC and A2.5 % beam tested on 7 days is presented in figure 9. Upon applying the load, the deflection at the mid-span of the beam was initially minimum. Once the cracks occurred in the beam along with the yielding of steel, the deflection drastically increased. The CC beam started to crack at 20 kN, whereas the A2.5 % beam started to crack at 35 kN. This indicates that the first cracking load of the A2.5 % beam was 75 % higher than the CC beam. According to IS: 456-2000 [48], the deflection of the all the horizontal members should not exceed the span/250, accordingly, the deflection of the tested beams is within the specified limits. The ultimate load of the CC beam was 35kN with a maximum deflection of 0.66 mm and the ultimate load of the A2.5 % beam was 55 kN with a maximum deflection of 0.31 mm. It was estimated that the maximum deflection of the beam was reduced by 53 % with addition of an accelerator. This demonstrates that the load-carrying capacity of the high-volume fly ash can be improved along with reduced deflection by the addition of an accelerator in earlier days. Raj and Rao [56] achieved the 40 % improvement in load carrying capacity of the beam with replacement of fly ash by 30 % with maximum deflection of 9.93mm. Hashmi et al. [54]

reported that the mid-span deflection of the beam was reduces from 21.8 mm-14.5 mm as the replacement of fly ash by cement 0 to 60 %. As compared to the outcomes of Hashmi et al. [54] and Raj and Rao [56], the deflection of the beam was reduced by more than 100 % with replacement of cement by 50 % fly ash along with addition of only 2.5 % of the accelerator at 7 days. The plastic region in the load-deflection behavior of the A2.5 % beam was more than the CC beam as presented in Figure 9.

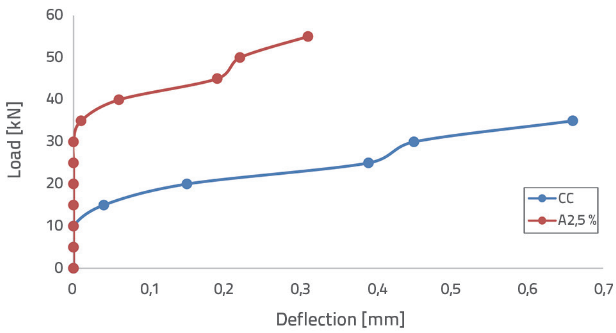

Figure 9. Load vs. deflection

4.7.3. Ductility

The ductility behavior of the beam was evaluated utilizing the deflection value at yield and ultimate stage. ACI committee-363 defined the ductility ratio as the ratio of ultimate and yield deflection. Ductility is defined as the ability of the material to undergo large deformation before failure. The beam with higher ductility ratio defines that the beam can withstand high deflection than the beam with a low ductility value. Ashour et al. [61] recommended that a ductility ratio of higher than 3 is essential for the sufficient ductility and moment distribution of the beam. Accordingly, all the tested beams possess a ductility ratio higher than 3. The ductility ratio of the CC beam was 7, whereas the ductility ratio of the A2.5 % beam was 13. The curve CC beam continues until the load drops sharply at around 0.6 mm deflection as shown in Figure 9. This rapid drop indicates the point of failure for the CC specimen. The A2.5 % specimen's curve plateaus after reaching its peak load around 0.35 mm deflection. This plateau represents significant plastic deformation before failure. The curve continues until it drops sharply at around 0.55 mm deflection. The A2.5 % beam specimen exhibits higher ductility compared to the CC specimen, as indicated by its longer plateau and slightly higher ultimate deflection. This suggests that the addition of 2.5 % of accelerator improves the material's ability to undergo plastic deformation before failure within 7 days.

4.7.4 Crack characteristics

The flexure cracks were observed on the zone of pure bending moment because the tensile strain of the concrete reached the maximum strain values. After the cracking started in the CC beam at bottom of mid-span of the beam as presented in Figure. 10, the flexure cracks were visible which grew vertically upward. Few inclined flexure shear cracks are formed, but no visible cracks were observed at the region of support for the A2.5 % beam. There were no diagonal cracks formed on the shear span. Finally, the beam failed with widening of cracks and with the crushing of concrete. Both CC and A2.5 % beam exhibit the same crack development; however, the number of cracks in the A2.5 % beam was higher than the CC beam. The number of cracks observed in the CC beam was 18, whereas the number of cracks in the A2.5 % beam was 22. Though, the number of cracks in the A2.5 % beam was higher whereas the width was less than the CC beam. The crack width of the A2.5 % beam at service and the ultimate stage was 0.05mm and 8.5mm, whereas the crack width of the CC beam at service and ultimate stage was 0.06mm and 6.8mm. The wider cracks in the beam essentially reduced the stiffness and promoted the penetration of the harmful substance in the beam. The crack width for the A2.5 % beam was 20 % lesser than the crack width of the CC beam. This is because of low heat of hydration that could facilitate capillary stress and internal crack, thereby positively affecting the strength development of concrete [62]. However, for all the series of beams investigated, the crack width at the service stage was within the permissible limit as per IS 456:2000 [48]. Because of the compressive strength of the fly ash concrete, the sudden failure was observed for the CC beam as compared to A2.5 % beam.

4.7.5. Strain distribution

The compressive strain on the top surface of the beam was noted at every load increment. The strain distribution of the beam against load for the concrete at 7 days is shown in Figure 11. At the service stage, the compressive strain of the CC beam was 1253 x 10^{-6}. The compressive strain at the ultimate stage for the HVFA beam was 5010 x 10^{-6}. At the service stage, the compressive strain of the A2.5 % beam was 825 x 10^{-6}. The compressive strain at ultimate stage for the A2.5 % beam was 4870 x 10^{-6}. This demonstrates that the HVFA concrete can accomplish its full strain capacity under flexural loading. The higher strain was observed in the CC beam, because of its lower elastic modulus and split tensile strength than the A2.5 % beam. There were more plastic strains in the A2.5 % beam, as the concrete is highly strong and

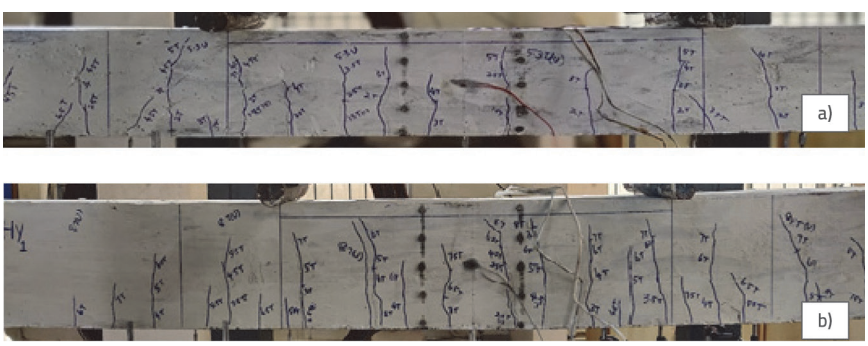

Figure 10. Crack characteristic of: a) CC beam; b) A2.5 % beam

has high ultimate load, which can withstand high bending moment before failure, where the CC exhibits brittle failure.

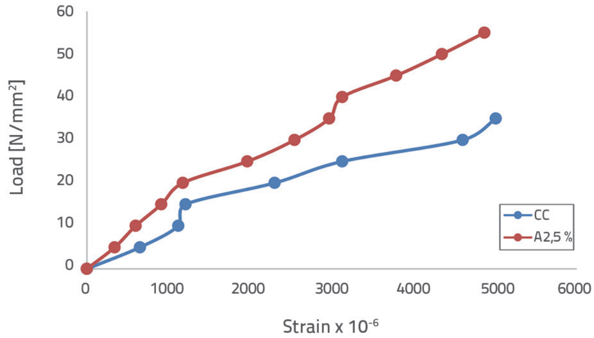

Figure 11. Load vs. strain

5. Conclusions

In recent days, the development of sustainable concrete, which is the idea of saving energy, safeguarding the environment and preservation of non-renewable resources has drawn wide consideration among researchers. The efficient way of sustainable development is to reduce the high consumption and utilization of natural resources. This study demonstrated the possibility of replacing cement with 50 % of fly ash to make sustainable concrete with improved properties. The various conclusions as drawn from the findings are as follows;

- The cement replaced with 50 % of fly ash along with accelerator addition drastically reduces the embodied energy by 34 % with enhanced concrete properties, i.e., mechanical and structural behavior.
- Use of fly ash and accelerator decreases the heat of hydration and setting time of the concrete at early ages; the calcium cation concentration in the accelerator boosts the low calcium content in the fly ash.
- The addition of accelerator in the fly ash concrete helps to achieve more than 45 % percentage of the target strength within 7 days of curing. The addition of accelerator increases the compressive strength, split tensile strength and flexural strength of the fly ash concrete by 68.3 %, 155 % and 21 % for 2.5 % addition of accelerator. Hence, the optimum dosage of accelerator for the HVFC was 2.5 %.
- The ultimate load carrying capacity of the beam was increased by 57 % with replacement of cement by 50 % fly ash along with addition of only 2.5 % of accelerator at 7 days. This is due to the utilization of an accelerator advancing the hydration process of reactive hauyne minerals, thus increasing the initial production of ettringite.
- The maximum deflection of the beam was reduced by 53 % with replacement of cement by 50 % fly ash along with addition of only 2.5 % of accelerator.
- The formation of wider cracks was avoided in the A2.5 % beam and delayed the occurrence of failure, thus improving the ductility behavior of the beam. The crack width of the A2.5 % beam was 20 % lesser than the crack width of the CC beam. The less crack width was due to the low heat of hydration.
- The BS-8110 accurately predicts the moment carrying capacity of CC and A2.5 % beam with average variation of 7.17 to 34.9 %.

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