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REVIEW ARTICLE–CIVIL ENGINEERING

Use of HVFA Concrete for Sustainable Development: A Comprehensive Review on Mechanical and Structural Properties

A. Fuzail Hashmi[1] · **M. Shariq**[2] · **A. Baqi**[2]

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Abstract

The rapid growth of concrete structures has led to high demand for cement production. However, the manufacturing of cement exhausts natural resources as well as emits an immense amount of CO_2 into the atmosphere, leading to global warming and other climatic impacts. Fly ash has been used extensively or as an additive in the cement industry. High volume fly ash (HVFA) concrete has numerous benefits in both the fresh and hardened states. It improves the workability and paste flow behaviour of the fresh concrete as well as enhances the durability and ultimate strength of the hardened concrete. Owing to its good mechanical and structural behaviour in harsh environmental conditions, HVFA concrete could be safely incorporated in reinforced concrete beams, columns, slabs, etc. The present paper has attempted to review various properties of HVFA concrete with respect to the heat of hydration, setting time, workability, porosity, chemical and corrosion resistance, mechanical properties, structural behaviour, and creep and shrinkage characteristics of HVFA concrete. Furthermore, the literature review revealed that more experimental and analytical research is yet to be carried out to effectively evaluate the durability aspects and long-term properties, i.e. creep and shrinkage behaviour of structural or reinforced elements of HVFA concrete.

Keywords Sustainable concrete · High volume fly ash · Mechanical properties · Structural properties · Creep and shrinkage

1 Introduction

Fly ash is the principal by-product of coal combustion in thermal power plants, and major electricity production is achieved through such power plants [1]. Currently, developing countries and most of the developed countries like China, India, the USA, and Japan are still using it and are largely dependent on coal-fired power plants to produce electricity. Coal is the single largest power source on earth accountable for producing more than three-quarters of the world's coal-fired electricity [2, 3]. Many countries are presently reliant on coal-fired power plants to generate electricity, resulting in considerable fly ash generation. Therefore, it becomes a necessity to utilize coal fly ash efficiently to minimize environmental pollution [4]. The disposal of fly ash is a significant environmental challenge because it contains toxic elements like selenium, chromium, and mercury, which is a potential hazard for the terrestrial and aquatic ecosystem. However, this industrial waste does have some valuable properties like pozzolanic and cementitious character. One of the novel ways of utilizing fly ash is in the construction industry, primarily as a substitute for cement. In India, fly ash blended cement is readily available, and up to 35% fly ash blended cement is generally used in concrete for the construction of buildings, roads, and other structures. Attempts are made to maximize the contribution of fly ash in the concrete, and positive results support it. Besides the construction industry, fly ash has also been utilized in various other fields such as zeolite synthesis, mine reclamation, adsorbents for mercury removal, carbon dioxide capture, filler in polymers, alumina, and cenosphere recovery [5–7]. The utilization of fly ash in various sectors is shown in Fig. 1. The use of fly ash as a partial replacement of cement in concrete is resourceful in reduction in cement costs, curbing the environmental hazards, saving energy, and resource conservation [8, 9]. It improves the workability and durability characteristics of concrete, minimizes the shrinkage, i.e. thermal and drying, as well as provides resistance

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✉ A. Fuzail Hashmi
fuzailhashmi121@gmail.com

[1] Civil Engineering Section, University Polytechnic, Faculty of Engineering and Technology, Aligarh Muslim University, Aligarh, India

[2] Department of Civil Engineering, Z.H. College of Engineering & Technology, Aligarh Muslim University, Aligarh, India

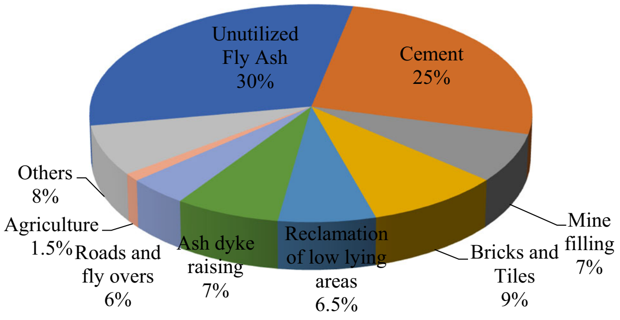


Fig. 1 Utilization of fly ash in different sectors [5]

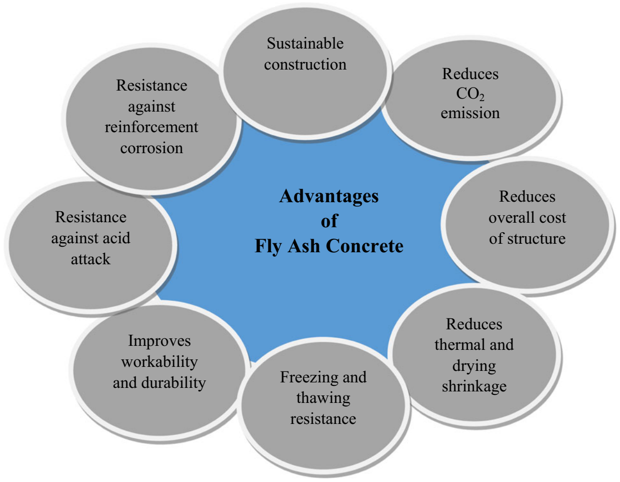


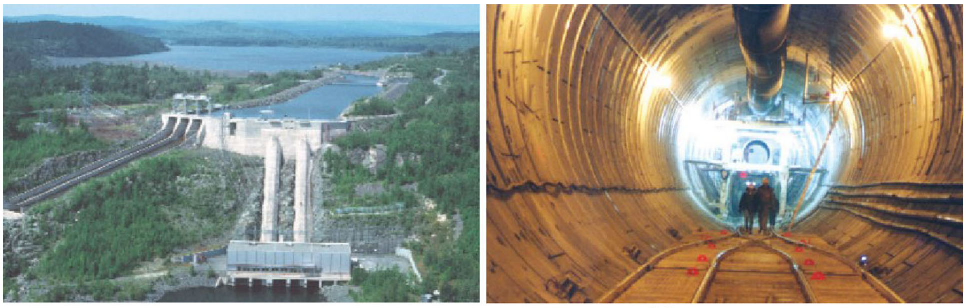
Fig. 2 Schematic view of the advantages of using fly ash in concrete

against corrosion, sulphate attack, and alkali-silica expansion [10, 11]. The advantages of fly ash in different concrete sectors are shown in Fig. 2. Despite various benefits of using fly ash, 100% utilization in the construction industry has not been possible due to some limitations [12].

Numerous work related to the utilization of fly ash in the construction industry has been carried out to assess the behaviour and properties of fly ash concrete [10–13]. In order to maximize the use of fly ash in concrete, high content of fly ash is added, whereby high volume fly ash (HVFA) concrete is produced. Some researchers [14–17] asserted mixing of more than 40% fly ash content to be called HVFA concrete. According to Dunstan et al. [16], HVFA concrete is defined as concrete that contains more than 40% fly ash. Bilodeau and Malhotra [17] suggested the fly ash concentration in concrete should be 50–70% with fly ash in a more significant concentration than cement in concrete. Few projects such as the housing development project (Hubli, Karnataka), Township development (Pune, Maharashtra), Rajasthan Atomic Power project, construction of pavements, etc. in which HVFA concrete has been used are running successfully [18]. The investigation carried out in various countries revealed that HVFA concrete is gaining popularity in the construction field. Some important projects (shown in Fig. 3) like Lower Notch Dam, York University Building (Canada), Seismic Rehabilitation of Barker Hall (Berkeley, USA), Park Lane Hotel, Residential Building (San Francisco, USA), etc. are constructed using HVFA concrete [19, 20].

Fly ash has been successfully used in self-compacting and roller compacted concrete over the past few decades [21, 22]. Roller-compacted concrete (RCC) is a zero-slump concrete with essentially the same ingredients as conventional concrete but in different ratios and increasingly with partial fly ash substitution for Portland cement. The RCC is mixed at a central plant, usually a pug mill mixing machine, and transported to the building site in non-agitated haul trucks. Adamu et al. [21] reported that optimized HVFA RCC mix could be achieved by partially replacing 10% fine aggregate with crumb rubber, 53% of cement with fly ash by volume and the addition of 1.2% nano-silica by weight of cementitious materials. Numerous studies have shown that using HVFA and crumb rubber as fine aggregate in RCC has several benefits, including increased toughness and energy absorption, reduced brittleness, improved fatigue life, increased thermal conductivity, improved sound absorption, and a significant reduction in the rate of crack propagation under flexural and tensile loading [23, 24]. Fly ash is increasingly used in RCC applications due to its several benefits, including lower total costs, greater long-term strength and durability, and less thermal temperature rise during mixing [25]. Another use of fly ash is in self-compacting concrete (SCC), a special type of concrete that can be placed and consolidated under its weight without any vibration because of its excellent deformability. SCC has received widespread recognition across the world. It mitigates the problems generated by noise and compaction compared to regular vibrating concrete [22]. Furthermore, the use of SCC has reduced the total duration of concrete construction in the majority of civil engineering projects [26]. Because of its superior fresh properties, it has sufficient viscosity to manage bleeding and segregation while flowing at a uniform level under gravity [27]. Particle size, textural characteristics, binder behaviour, aggregate type, and w/b ratio are some of the parameters that influence the workability of HVFA-based SCC [27, 28]. Slump flows for Portland cement substitutions more than 50% with fly ash were found to be lower when compared to SCC mixes created with less than 50% replacement levels [29]. Nguyen et al. [30] reported the strength of SCC dropped with the incorporation of fly ash ($\geq$ 30%) at early ages but increases at later ages. It was observed that the use of metakaolin, silica fume, and gypsum enhanced the strength of SCC for all curing ages.

Digital construction has become the subject of rapidly growing research activities globally because of its benefits in terms of higher construction quality and productivity, higher geometric shapes freedom, more effective use of natural resources, and higher cost-efficiency [31, 32]. In response



(a) Lower Notch Dam

(b) St. Clair river tunnel

(c) York University, computer science building

(d) Bay view high rise apartment

Fig. 3 Some important concrete structures constructed using HVFA concrete [20]

to the growing number of development initiatives and practical applications, many methods involving the 3D printing of concrete have been created. The critical problem in developing a printable mix is creating a thixotropic material that is readily extrudable during the printing process while retaining its original form after deposition. Most 3D printed binders employ Portland cement as the primary constituent in their compositions because of its inherent thixotropic characteristic. Le et al. [33] demonstrated a 3D-printed high strength mortar with sand: binder ratio of 3:2, 70% Portland cement, 20% fly ash, and 10% silica fume, as well as micropolypropylene fibres. A small addition of nanoclay in high volume fly ash mixes can effectively improve the thixotropy of concrete [33–36]. The resulting mixes reduce the environmental impact of traditional concrete mixes involving Portland cement and present a suitable formulation for 3D printing applications. Kondepudi and Subramaniam [37] developed a printable alkali-activated fly ash mixture by adding microsilica and clay and found that the resulting mixture provided a good homogeneous flow under pressure. Panda et al. [38] investigated the use of highly purified attapulgite nanoclay in high volume fly ash mixes. Results showed that the addition of nano-silica significantly improved the thixotropic property of HVFA mixes, thus increasing its suitability for concrete printing applications.

In the present paper, various properties of HVFA concrete such as hydration heat, setting time, work-ability, abrasion resistance, porosity and water absorption, and chemical and corrosion resistance with the fly ash types followed by the utilization have been reviewed. Further, the mechanical (compressive, tensile, static modulus of elasticity) and structural properties along with creep and shrinkage strain and non-destructive testing techniques, flexural performance, and long-term behaviour have also been reviewed. All these properties from the past studies are collected to get comprehensive information regarding various aspects of HVFA concrete which would be helpful to the practising engineers and designers for the design of concrete structures containing higher volumes of fly ash. Numerous work has been carried out on nanomaterials and fly ash, long-term creep and shrinkage characteristics of HVFA concrete, but there is limited study available on the structural elements of HVFA concrete, i.e. full-scale reinforced concrete beams, slabs, columns etc.

1.1 Types and Classification of Fly Ash

As per the American Society for Testing and Materials (ASTM) standard, fly ash can be classified as Class C and Class F depending on the type and characteristics of coal from which it is produced. Fly ash is generally obtained from the following types of coal.

- Lignite coal is referred to as soft brown coal formed at shallow depths at a temperature of around 100 °C. It contains high moisture and is regarded as the lowest rank of coal.
- Sub-bituminous coal is considered low-grade coal having 35–45% of carbon concentrations. The properties of this coal vary between bituminous and lignite coal. It is formed when the lignite coal becomes darker and more complex with time.

Table 1 Elements present in class F and class C fly ash

Components	Class F (%)	Class C (%)
SiO_2	37–62	12–46
Al_2O_3	16–35	2–20
Fe_2O_3	2–21	16–35
CaO	0.5–14.0	15–55
MgO	0.3–5.0	0.1–6.5
K_2O	0.1–4.0	0.3–9.5
Na_2O	0.1–3.5	0.2–2.5
Loss on Ignition (LOI)	0.3–32.0	0.3–12.0

- Bituminous coal is black and flammable of relatively good quality compared to lignite but less than anthracite. It has a higher percentage of carbonaceous matter.
- Anthracite coal is hard, compact and has high density with 92–98% of carbon with fewer impurities. It is considered as the highest rank coal with utmost calorific value.

Class F fly ash is produced from burning anthracite and bituminous coal. This fly ash has shallow calcium content, i.e. less than 5% [39]. It possesses pozzolanic behaviour when reacted with calcium hydroxide and water. Class C fly ash is derived from the burning of lignite and sub-bituminous coal, and it possesses high content of calcium (above 25%) and magnesium [39]. These fly ashes contain some self-cementitious properties along with pozzolanic characteristics [40, 41].

The concentration of silicon dioxide (SiO_2) and aluminium oxide (Al_2O_3) is relatively higher in Class F with lesser contents of iron oxide (Fe_2O_3) [42]. In comparison with Class F fly ash, Class C fly ash has a more crystalline structure consisting of calcium aluminate, sulphur-bearing minerals (anhydrite), and calcium oxide [43]. The particles of Class C and Class F fly ashes are usually spherical, ranging from 2 to 10 μm, and are primarily composed of Si_2O_3 and Fe_2O_3 [44, 45]. Heavy metals such as nickel, cadmium, vanadium, chromium, barium, zinc, and lead are also found in lesser amounts in fly ash. Some fly ash particles vary from less than μm to more than 100 μm with an average size usually under 20 μm [45]. The range of various elements present in Class C and Class F fly ash is shown in Table 1. It has been observed that the same type of fly ash has a wide range of elements due to the variation in sources and processing conditions of fly ash.

Fly ash is also classified based on IS codes and boiler operations. According to IS 3812 [46], fly ash is classified as, i.e. Grade I and Grade II. Grade I fly ash is derived from bituminous coal with fractions of $SiO_2 + Al_2O_3 + Fe_2O_3$ greater than 70%, whereas Grade II fly ash is derived from lignite coal having fractions $SiO_2 + Al_2O_3 + Fe_2O_3$ greater than 50%. Based on boiler operations, fly ash is classified as low-temperature and high-temperature fly ash. Low-temperature fly ash is produced when the combustion temperature is below 900 °C, and high-temperature fly ash is generated at 1000 °C. Comprehensive knowledge of the properties of various types of fly ash and their hydration mechanisms would increase the fundamental understanding of employing fly ash in concrete in a more scientific manner [47]. With developments in characterization techniques such as X-ray diffractometers, thermogravimetric analysers, and scanning electron microscopy, it is now feasible to examine fly ash for chemical and physical properties in order to more efficiently utilize it. Furthermore, understanding the hydration mechanism of fly ash in cement and its correlation with property development via these advanced techniques enables intervention of the hydration mechanism either physically (primarily through size reduction) or chemically (incorporating nanomaterials) to increase the efficiency of fly ash in concrete.

1.2 Utilization of Fly Ash

Nowadays, fly ash is widely used as a substitute for material in the construction industry or as an additive in the cement industry. Around 50% of fly ash has been utilized in the cement and construction industry [13]. Class C fly ash with a high content of lime possesses suitable cementitious property along with the pozzolanic activity. Fly ash's pozzolanic properties make it an excellent material for cement substitution and other construction purposes. The addition of fly ash to the cement in the concrete mix reduces the amount of water required thereby lowering the cost of concrete buildings. Tiny spherical particles of fly ash help reduce the air entrainment in the concrete [48]. Fly ash is well mixed with the cement and, protects against corrosion, acid attack, and imparts later age strength to the concrete [49]. In the last few decades, an innovative construction material, i.e. fly ash-based geopolymer concrete, has emerged as a good alternative in the construction industry. The mix of geopolymer concrete is prepared without any addition of cement, and the binding property is provided by aluminate and silicate bearing materials with a caustic activator. Fly ash is also utilized as an additional aluminium source and amorphous additives to modify the silica-alumina ratio, which helps in improving the geopolymerization process [44, 50]. Fly ash has also been used in the manufacturing of bricks. The percentage of clay in the brick can be replaced by fly ash, and some studies have shown that 100% fly ash brick can also be prepared [51]. Such bricks show better results in terms of compressive

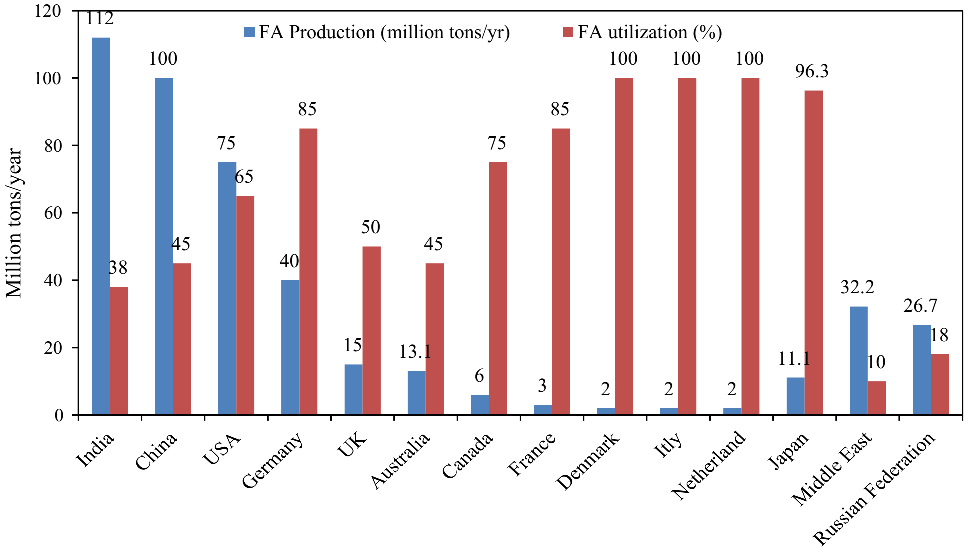


Fig. 4 Worldwide fly ash production and utilization [57]

strength and are more durable than the standard burnt clay bricks. Fly ash has also shown several benefits when mixed with soil. It enhances soil properties, reduces the formation of crust, and decreases the activity of metals in the ground [52]. Fly ash contains essential macronutrients such as calcium, magnesium, potassium, sulphur, phosphorus, and micronutrients like iron, zinc, manganese, copper, etc. [53]. Class C fly ash containing more than 50% silicon dioxide, aluminium oxide, and iron oxide is generally used to manufacture high strength and acid-resistant glass ceramics [54, 55]. Fly ash has been extensively used as a filling material in mining areas and construction sites, highway embankments, over-bridges, etc., due to accessibility and being a cheaper material compared to other filling materials.

In the context of the economic aspect, the use of fly ash in place of cement is demonstrated to be a highly cost-effective technology with a promising waste management approach instead of its direct disposal to the environment. Coal is an important source of energy all around the globe. Coal supplied 29% of global energy; despite increased usage of renewables, the percentage of coal is predicted to remain around 24% by 2035. Because worldwide energy consumption is predicted to rise by 30% by 2035, the quantity of fly ash used per year will rise from 3840 million tons in 2015 to 4032 million tons in 2035 [56]. China was the world's biggest coal user in 2015 (50% of worldwide demand) and is anticipated to remain so in 2035, accounting for 47% of global coal consumption. Figure 4 depicts the worldwide production and usage of coal fly ash. The top two producers, India and China, have utilization rates of less than 50%, whereas Denmark, Italy, and the Netherlands have resource utilization of 100%. [57].

2 General Properties of Fly Ash Concrete

The properties of the concrete mix containing fly ash are affected due to the composition, lime content, and fineness [23]. In both fresh and hardened phases, the addition of fly ash to the cement improves the performance of the concrete. Adding fly ash generally benefits fresh concrete by reducing water requirements, improving workability, hydration heat, etc. [58, 59]. The fly ash particles are spherical and act as tiny balls in the concrete mix, thereby providing a lubricant effect. The pumpability of concrete also gets improved by reducing frictional losses during the pumping process. Fly ash also helps in lowering drying shrinkage and cracking during the concreting [49]. In a hardened state, fly ash reacts with available lime and alkali in the concrete mix to yield additional cementitious compounds, i.e. calcium silicate hydrate (C–S–H).

$$\text{Cement reaction}: \ C_3S\ (\text{hydration}) \rightarrow C{-}S{-}H + CaOH$$

$$\text{Pozzolanic reaction}: \ CaOH + S\ \left(\text{silica from fly ash}\right) \rightarrow C{-}S{-}H$$

The additional binder obtained during fly ash reaction allows the concrete to gain strength with time, thereby increasing the ultimate strength of concrete at later ages. The decrease in water content along with the formation of C–S–H compounds in fly ash concrete reduces the pore interconnectivity of the concrete, as a result of which permeability gets reduced. The reduction in permeability enhances the durability of the concrete and improves corrosion resistance. Fly ash improves the resistance to sulphate and acid attack by reacting with available alkali and free lime and thus making it unavailable to respond with sulphate and other certain minerals.

2.1 Heat of Hydration

Recent research has proved that the hydration heat in the concrete mix is reduced when the cement is partially replaced with fly ash. The higher the cement replacement by fly ash, the lower the fly ash concrete's temperature. Poon et al. [58] and Li et al. [59] observed the reduction in the heat of hydration when over 40% Class C fly ash was added to the concrete mix. Atis and Duran [60] marked a decline in the temperature rise while 50 and 70% of cement were replaced with fly ash. Bentz et al. [61] observed a substantial decrease in the heat of hydration in comparison to the conventional concrete mix when 60% Class C fly ash was replaced by cement. Fly ash retards the hydration of cement significantly at high water–cement ratios [62]. Haustein et al. [63] reported a decrease in heat generation rate in fly ash concrete compared to the controlled concrete mix. According to Snelson et al. [64], fly ash reduces heat production significantly. Termkhajornkit et al. [65] investigated the curing of fly ash concrete and discovered that water improves the hydration of fly ash particles. Retardation in the heat of hydration has been reported in various studies on the fly ash concrete mix [66, 67]. Matos et al. [68] described that fly ash in the concrete was effective in mass concreting by reducing the temperature due to the low heat output. The increase in fly ash content significantly decreased the temperature rise. Low heat of hydration in HVFA concrete is an advantage for reducing thermal stress in the concrete. The heat of hydration is influenced mainly by the proportion of tricalcium silicate (C_3S) and dicalcium silicate (C_2A) in the cement along with water-cement ratio, fly ash content, fineness, and curing temperature. The cumulative heat evolution was reduced by partially substituting cement with fly ash. Xin et al. [69] investigated the effectiveness of fly ash in reducing the thermal stress of concrete with different fly ash replacement levels (0%, 20%, 50%, and 80%). Results showed that fly ash replacement level with 50% showed a desirable effect on reducing the thermal stress. Active utilization of fly ash in the concrete improved the performance of concrete by reducing the thermal stresses in the concrete [70]. Mimura et al. [71] reported that fly ash concrete has lesser thermal stress than controlled cement concrete. Yoshitake et al. [72] studied the thermal and mechanical properties of HVFA concrete having 50% replacement of cement by fly ash. The favourable thermal properties in HVFA concrete were obtained contributing to decreased thermal stress.

Thus, from the past studies, fly ash in the concrete mix has been beneficial as it considerably reduces the thermal stress and heat of hydration in the concrete paste, which is an excellent advantage in mass concreting, especially in hot weather conditions.

2.2 Setting Time

Many researchers [73–77] have stated that adding fly ash to the concrete mix enhanced the concrete's initial and final setting times. The initial and final setting time of concrete mix increases with the addition of high amount of fly ash. When 60% fly ash was added to the concrete mix, Mirza et al. [74] noted that it took longer for the concrete to set. The concrete's initial and ultimate setting times containing fly ash were comparatively higher than the conventional concrete [75–78]. Hassani et al. [79] conducted an experimental study to improve the setting times of the concrete mix using Class F fly ash. Liu et al. [80] suggested that adding fly ash in the mix delayed the setting of the concrete mix. Jovanovic et al. [81] did an experimental investigation in the cement mixtures containing various percentages of fly ash up to 90%. It was found that the fly ash delayed the initial setting time of the cement mixtures, and the highest setting time was identified in the 90% fly ash content. The setting time of the cement paste is affected by the inclusion of different calcium content of fly ash [82, 83]. Figure 5 compares the initial setting time of ordinary Portland cement (OPC) and fly ash concrete. Thus, it has been observed that fly ash in the cement mixtures resulted in a significant increase in the initial and final setting times. Additionally, it is directly related to the quantity of fly ash in the paste.

2.3 Workability

Good workability of concrete is always desired for easy workmanship and better compaction. It has been observed that fly ash changes the microstructure of the paste and increases the workability of concrete [84]. Sahmaran and Yaman [85] reported a 23% increase in slump value when the cement was partially replaced by 50% Class C fly ash. The addition of fly ash in the concrete as an admixture progresses the workability of concrete [86]. In a critical assessment of fly ash concrete, Berry and Malhotra [87] discovered increased workability, pumpability, cohesion, ultimate strength, and durability. Replacement of cement by Class F fly ash significantly increases concrete workability [41, 88]. Balakrishnan and Awal [89] reported that the cement paste's workability depends on the content of fly ash. Saravanakumar and Dhinakaran [90] observed a 13–18% increase in the slump with the rise in workability when 50–60% fly ash was added to the mixture. Figure 6 shows that the workability of the concrete

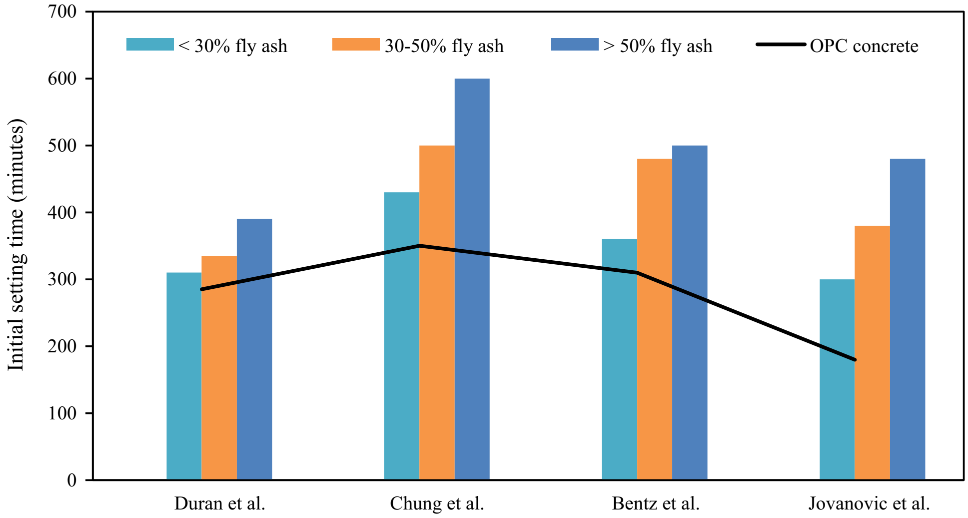


Fig. 5 Comparison of initial setting time between OPC and fly ash concrete [73, 75, 76, 81]

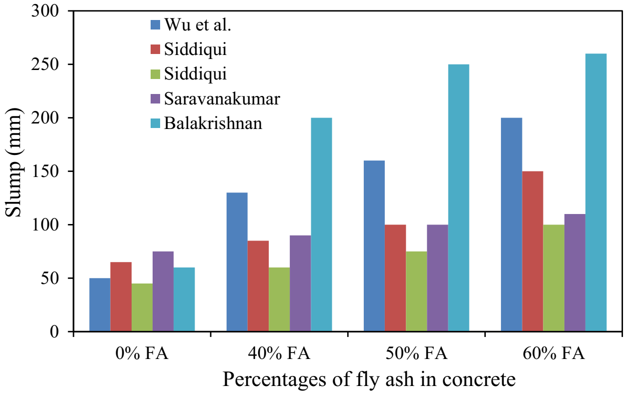


Fig. 6 Workability of concrete having different fly ash content [41, 88–91]

increases with the increment in fly ash content in the concrete mixtures. Some past studies [92–95] reported that the workability of fly ash concrete was enhanced considerably when high volumes of fly ash were added to the concrete mix. Fly ash in the concrete helps in reducing the demand for superplasticizers and admixtures to achieve the required workability [96, 97]. The spherical-shaped particles of fly ash act as miniature ball bearings within the concrete mix, thereby improving concrete workability and finish-ability. Thus, from past studies, it can be concluded that fly ash is a resourceful material which has good utility in increasing the workability of the concrete.

2.4 Abrasion Resistance

The abrasion resistance of concrete is directly related to the compressive strength of concrete and increases with the concrete age [98]. However, it is observed that abrasion resistance decreases by replacing cement with fly ash. Siddiqui [88, 99] noticed a reduction by 73%, 35%, and 37% after 7, 28, and 56 days, respectively, in the abrasion resistance of concrete specimens while adding 50% Class F fly ash in the concrete. The substitution of 50 to 60% low calcium content fly ash in the concrete resulted in a significant decrease in the abrasion resistance of concrete [100]. Jiang et al. [101] remarked that fly ash concrete with 30 to 50% cement supplementation had lower abrasion resistance than ordinary concrete. The concrete's compressive strength significantly impacts its abrasion resistance regardless of fly ash concentration. Traditional concrete outperformed HVFA concrete in terms of abrasion resistance, especially at high compressive strengths [102]. With the addition of 50% of cement by fly ash, Langan et al. [103] found that the abrasion resistance of concrete specimens was reduced. Nassar [104] investigated the abrasion resistance of 25% and 50% Class C fly ash, respectively. In contrast with samples containing 50% fly ash, those containing 25% fly ash demonstrated excellent abrasion resistance. Most studies reveal that the abrasion resistance of HVFA concrete is strongly affected by the concrete's compressive strength and declines as the fly ash concentration increases, particularly beyond 30%.

2.5 Porosity and Water Absorption

Porosity and water absorption play a significant part in the degradation of concrete structures since chlorides and sulphate attack the concrete in contact with water, causing it to deteriorate. Porosity impacts the strength and durability of concrete structures as lower porosity increases the strength of concrete structures. Fly ash concrete has a greater porosity than conventional concrete [98]. The apparent porosity and water absorption of the concrete containing Class C and Class F fly ashes increase with the increase in the fly ash content [105, 106]. With 60% fly ash inclusion, Mardani and

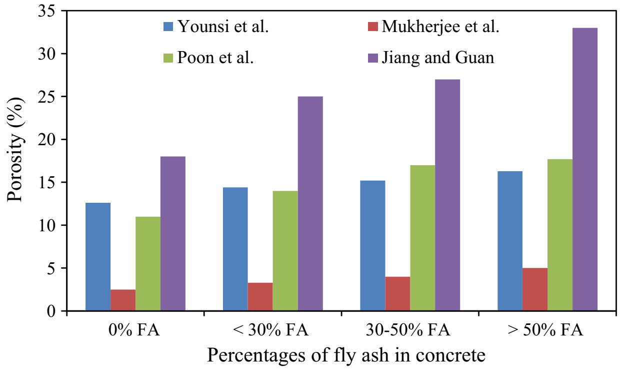


Fig. 7 Comparison of porosity of different content of fly ash concrete [57, 105, 106, 112]

Ramyar [107] found that the proportion of water absorption and permeability void of concrete specimens improved by up to 34%. Poon et al. [58] found an increment in the porosity of paste specimens by 16% and 47% at 28 and 90 days when cement with 45% Class C fly ash was substituted. Few studies [108–110] also revealed that fly ash in the concrete significantly increased the porosity of the concrete. The porosity depends upon several factors such as percentage of fly ash, water–cement ratio, admixtures, a reaction between aggregates, and hydrated cement paste. Lammertijn and Belie [111] studied the effects of fly ash at different replacement levels and reported that the porosity of the concrete increased with the increasing fly ash content. Jiang and Guan [112] reported a 40–60% increment in porosity up to 90 days when 50% Class C fly ash was added to the concrete. With the addition of 70% fly ash to the concrete, Silva and Brito [113] found a decrease in capillarity water absorption. The comparison of the porosity of different percentages of fly ash concrete is shown in Fig. 7. From the literature, it can be concluded that the porosity and water absorption of concrete increased with increasing the fly ash content.

2.6 Chemical and Corrosion Resistance

The use of fly ash as a partial replacement for cement in concrete provides resistance against chemical attack and protects reinforcement against corrosion. The durability of concrete has increasingly been a focus of substantial research worldwide because of the early cracking of a significant number of reinforced concrete structures. The infiltration of chloride ions (Cl) is the primary cause of steel corrosion in concrete. Chung et al. [114] suggested adding supplementary cementitious materials to concrete, i.e. fly ash. Such materials have a favourable impact on the pore structure of the concrete by improving the resistance to carbonation and Cl diffusion. [115, 116]. Xie et al. [117] reported improved carbonation resistance of concrete containing fly ash at low W/B, i.e. $W/B \leq 0.35$, whereas the carbonation resistance for high-W/B, i.e. $W/B > 0.5$, the resistance was reduced. It was also revealed that early carbonation modifies the concrete's interior pore structure and increases its capacity to resist Cl diffusion. Liu et al.[118] reported that carbonation alters the chloride ingress profile, lowers the chloride binding capacity, and speeds up the rate of chloride ion diffusion in the fly ash concrete. Glinicki [119] discovered a significant increase in fly ash to chloride ion penetration in concrete resistivity. Increased fly ash replacement levels resulted in improved resistance with cure time. Concrete made using blended cement and fly ash had a deeper level of carbonation than Portland cement concrete. Liu [120] reported that the water-to-cement ratio and fly ash content largely impact the chloride binding capacity and the diffusion coefficient.

Concrete constructions have been carried out in both regular and extreme environments. Regular maintenance of structures is essential to extend its service life. Sulphate may be present in soil and industrial wastes, a significant source of damage to concrete structures. External sulphate ions react with hydration products, causing the concrete to expand, and the bond between paste and aggregate deteriorates [121]. Sulphate causes the production of thaumasite, ettringite, and gypsum, all of which contribute to concrete cracking, strength loss, and spalling. Many studies have found that fly ash concrete showed better than OPC concrete in terms of durability [122, 123]. Zawawi [124] proved that replacing 10% of the sand with fly ash resulted in higher mechanical properties and denser concrete having more resistance to sulphate attack than the control mix. Torii et al. [125] found that the 50% replacement of cement by Class C fly ash in the concrete was very effective in improving the sulphate resistance of concrete. The enhanced sulphate resistance of concrete having high fly ash content was attributed primarily to the lack of sulphate ion infiltration, resulting in less gypsum and ettringite production in concrete. Chindaprasirt et al. [126] studied the sulphate resistance of mortars made from ordinary Portland cement containing fly ash and ground rice husk ash and concluded that up to 40% of Portland cement could be replaced with these pozzolans in making blended cement with good sulphate resistance. Torri et al. [125] conducted an experimental study on fly ash concrete with up to 50% cement substitution by exposing concrete specimens to sodium sulphate for two years. The sulphate resistance of HVFA concrete sample had increased. Baert et al. [127] reported that 60% of fly ash concrete specimens showed better performance against sulphuric and acetic acid. Siddiqui and Khan [128] reported enhanced acid resistance with Class F fly ash. Balakrishnan and Awwal [89] studied the behaviour of the HVFA concrete in 2% HCl solution for 75 days. Higher percentage of fly ash showed lesser weight loss in the concrete. Incorporating higher volumes of Class C fly ash in the concrete significantly improved the sulphuric acid resistance of concrete [129]. Sun and Wu [130] tested various

Table 2 General properties of fly ash

Fly ash content	Effect of fly ash on different properties					
	Heat of hydration	Setting time	Workability	Abrasion resistance	Porosity	Chemical resistance
Less than 40%	–	Setting time increased [75]	Workability increased [41, 88]	Improvement in the resistance [102]	Porosity increased [109, 110]	Good resistance [135, 136]
40–50%	Retardation in heat of hydration [58]	Setting time increased [76]	Increase in slump value [41, 85, 88]	Reduction in abrasion [88, 99]	Porosity and water absorption increased [111]	Good sulphate resistance [125]
50–60%	Reduction in the rate of hydration [59–62]	Rise in the initial and final setting time [73, 74]	Increase in slump value [90]	Reduction in the resistance of concrete [100, 125]	Increment in the porosity [105, 112]	Good resistance against acid attack [127, 133]
More than 60%	Significant decrease in heat of hydration [71]	Rise in the setting time [81]	Workability increased [92–94]	–	Increment in the porosity [111, 135]	Improved resistance [129, 130]

concrete specimens of fly ash composition against sulphuric acid solution and found improved freeze–thaw resistance as well as chemical resistance. Sahoo et al. [131] reported increased resistance against salt, sulphate and acid attack when carbonated fly ash was incorporated in the concrete. Park [132] reported that the corrosion resistance of fly ash concrete was more than the conventional concrete. Choi et al. [133] investigated conventional and fly ash concrete under complete immersion in NaCl solution. Fly ash was found to have enhanced the corrosion resistance and decreased the permeability of chloride ions [134]. Several studies have also determined that fly ash concrete has high corrosion resistance [135–137]. Fly ash improves acid resistance to the concrete by consuming the free lime making it unavailable to react with sulphate. Fly ash reduces the permeability, which prevents sulphate penetration into the concrete and provides corrosion resistance to the concrete. Replacement of cement reduces the amount of reactive aluminates available. Thus, it can be concluded that fly ash concrete has a better resistance against acid attack and corrosion. The general properties of the fly ash concrete are presented in Table 2.

3 Mechanical Properties of HVFA Concrete

Various uses of fly ash in the concrete building and ceramic industry have been devised in several forms over several decades by mixing it with soil or binding materials such as cement. Various practical and theoretical research [138–145] have been conducted to replace fly ash with cement or aggregate content as an additive in concrete. However, the use of fly ash in concrete with a high volume percentage has been shown to alter mechanical characteristics such as age-dependent compressive and tensile strength, modulus of elasticity, elastic and long-term deflection (i.e. creep and shrinkage deflection). These essential characteristics affect reinforced and pre-stressed concrete's performance, durability as well as load-bearing capabilities.

3.1 Compressive Strength

HVFA concrete has considerably lower early age strength than cement due to the slower rate of pozzolanic reaction than cement hydration [139–141]. Many studies have demonstrated that equal or greater compressive strength may be obtained by lowering the w/c ratio and adding a superplasticizer to HVFA concrete [142, 143]. Huang [75] investigated different mechanical properties of HVFA concrete containing Class F fly ash and reported lower early age strength when compared to the conventional concrete mix. Replacing the Class C fly ash with both cement and sand enhances the strength values [75]. According to Shon et al. [144], the compressive strength of HVFA concrete reduces as the amount of Class F fly ash increases. Siddique [145] discovered that at all ages, the compressive strength of fly ash concrete mixes with 10%, 20%, 30%, 40%, and 50% fine aggregate substitution with Class F fly ash was greater than the control mix. Siddique [41] found that using 50% Class F fly ash as a cement substitute reduced the strength of concrete by 40%, 33%, 23%, and 18% at 7, 28, 91, and 365 days, respectively. HVFA concrete's compressive strength declined at all ages as the fly ash concentration increased. The compressive strength of fly ash concrete containing up to 50% cement replacement could be useful in most structural applications. Compared to ordinary concrete, HVFA concrete achieved adequate or greater compressive strength at later ages, according to Atis [102],

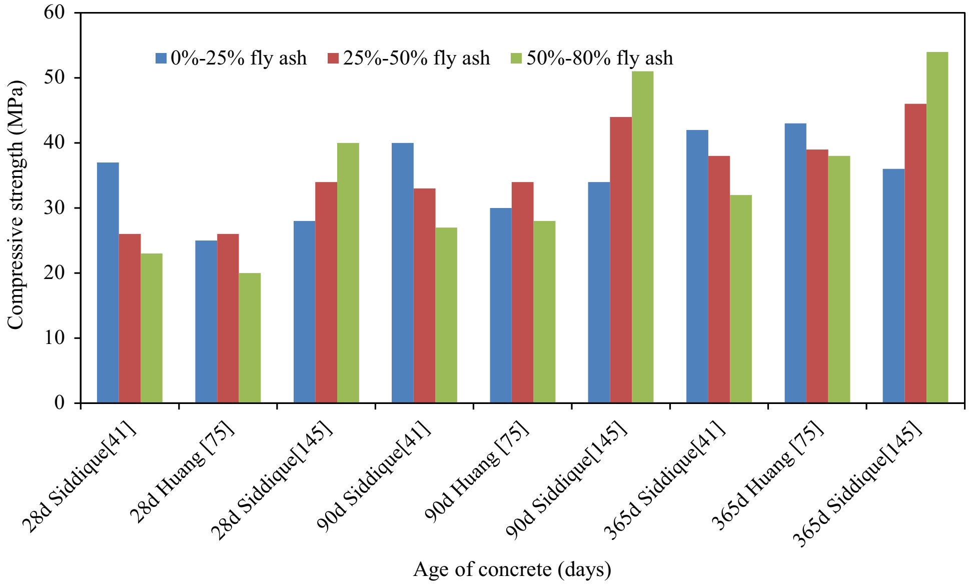


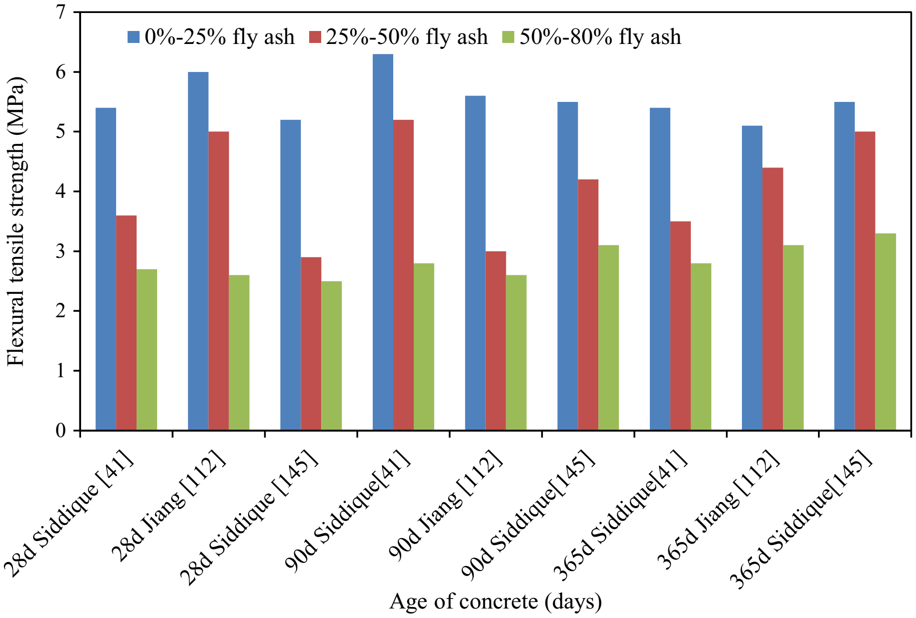
Fig. 8 Comparison of compressive strength of different percentages of fly ash concrete with the age of concrete [41, 75, 145]

although the pace of strength gain was slow at first. Nassar [104] measured compressive strength after 7, 28, and 90 days of wet curing. A blend with 25% Class C fly ash replacement was stronger than one with 50% fly ash replacement. However, as time progressed, the strength steadily increased. At an early stage, Wang and Park [139] discovered that the compressive strength of Class F fly ash blended concrete is lower than normal concrete. The compressive strength of fly ash concrete exceeds that of conventional concrete when 15% and 25% of fly ash were replaced in concrete. However, when 45% to 55% of fly ash was replaced in concrete, the compressive strength declined at higher *w*/*c* ratios. But for a less *w*/*c* ratio, it surpasses the strength of the conventional concrete. For lower cement replacement with fly ash, concrete mixtures can reach similar or higher compressive strength than conventional concrete at later ages, i.e. 56 days [146, 147]. Yazici et al. [148] found that utilizing Class C fly ash and GGBFS for steam and autoclave curing increased concrete compression strength. With 50% fly ash as cement replacement, Li et al. [58] found a 58%, 46%, 47%, 33%, 18%, 6%, 1%, and 5% loss in the compressive strength of concretes at 1, 3, 7, 28, 56, 112, 360, and 720 days, respectively. Misra et al. and Yoon et al. [149, 150] observed a reduction in concrete's 7, 28, and 90 days compressive strength while using 50% fly ash as cement replacement. Sumer [151] found that Class C fly ash has higher strength than Class F fly ash and can achieve further strength than Portland cement concrete at longer ages. The comparison of the compressive strength of fly ash concrete with the age of concrete derived from earlier research is shown in Fig. 8. From the above literature, it is concluded that the compressive strength of HVFA concrete is low at initial ages, particularly when the content of fly ash is above 40% but with the age of concrete, i.e. beyond 28 days, it gains adequate or better compressive strength as compared to conventional concrete.

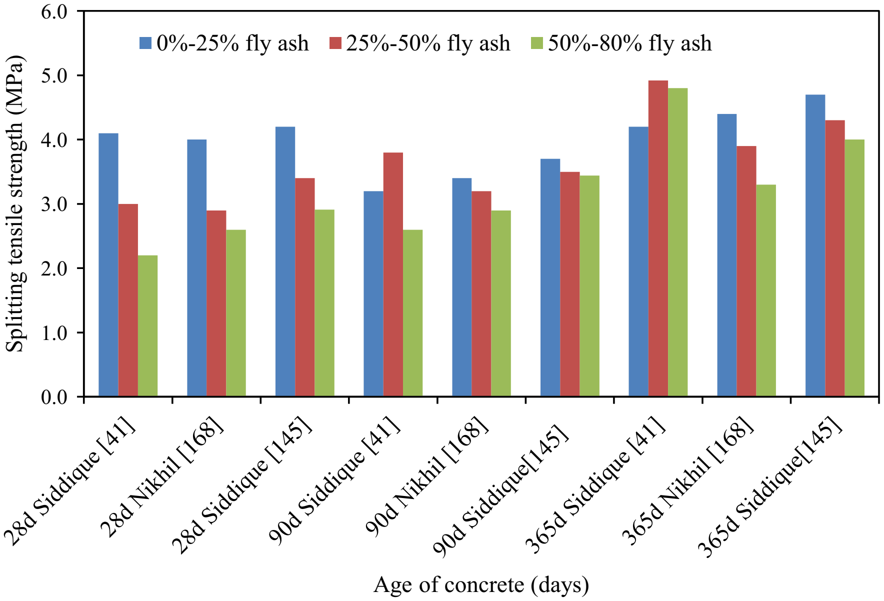
3.2 Tensile Strength

The tensile strength of concrete has a significant impact on the performance of reinforced concrete structures. The tensile strength can regulate deflection and flexural reinforcement in concrete structures. It increases the serviceability of flexural components by preventing cracking in concrete buildings [138]. According to Huang et al. [75], adding 50 to 80% of Class F fly ash to the concrete reduces its flexural strength. As the percentage of Class F fly ash increased, the flexural strength of the concrete dropped significantly during the early ages. Between 28 and 365 days, a significant rise in flexural strength was observed due to the pozzolanic action of the fly ash particles with respect to the age of the concrete. With 60% fly ash as cement replacement, Jiang et al. [112] observed a 20% loss in the flexural tensile strength of concrete containing low calcium fly ash at the age of 56 days. The flexural strength is affected due to the porosity and pore size distribution of the concrete mix. During early ages, the size of the pores is large in the fly ash concrete, but with respect to the age of concrete, the size of the pores decreases, resulting in the enhancement of flexural tensile strength. The addition of steel fibres in the fly ash concrete mix significantly improved the flexural tensile strength of concrete [165]. Naik et al. [166] investigated the flexural strength of concrete with 15–70% Class C fly ash and found an increase in the flexural strength of the concrete containing fly ash with age. Kumar et al. [100] adjusted the mixture by substituting up to 60% of the Class F fly ash. Three different *w*/*c* ratios were used to make the mixtures (0.30, 0.34, and 0.40). The fly ash

Fig. 9 Variation in flexural and splitting tensile strength of different percentages of fly ash concrete with age [41, 112, 145, 168]



(a) Flexural tensile strength



(b) Splitting tensile strength

mixes exhibited a constant reduction in flexural strength with increasing fly ash concentration for all *w*/*c* ratios. At 90 days and beyond, the mixes containing 40% fly ash demonstrated the greatest flexural strength. Siddique [41] investigated the characteristics of concrete by substituting Class F fly ash for 40%, 45%, and 50% of the cement and observed continuous growth of flexural strength with age.

The splitting tensile strength of HVFA concrete decreased as the percentage of fly ash in the mix increased [41, 88]. The comparison of the flexural and splitting tensile strength of fly ash concrete of some past studies with respect to the age of concrete is shown in Fig. 9a and b. Soni and Saini [167] reported a 75% and 53% drop at the 28 and 56 days splitting tensile strength with the inclusion of 50% fly ash as a cement replacement. The splitting tensile strength of the concrete mix containing 50% Class F fly ash is significantly reduced during early ages [85, 168]. Yoshitake et al. [169] found a 50%, 57%, 58%, 61%, 44%, 15%, and 3% drop in the splitting tensile strength of concrete at 1, 2, 3, 5, 7, 28, and 91 days with the inclusion of 50% Class F fly

Table 3 Effect of fly ash on mechanical properties of concrete

Compressive strength				
Fly ash (%)	Percentage gain or loss in fly ash concrete with respect to conventional concrete			
	28 days	90 days	180 days	365 days
30	− 10% [152], − 5% [154]	+ 8% [154]	+ 25% [154]	+ 14% [152]
35	− 32% [88]	–	–	–
40	+ 15% [75], − 28% [41]	+ 21% [75], − 10% [41]		+ 28% [75], − 4% [41]
45	− 8% [57], − 18% [60]	− 3% [57], − 13% [89]	–	–
50	− 37% [41], − 18% [155], − 32% [58], − 41% [62]	− 30% [41],		− 24% [41], − 0.9% [8]
55	− 38% [41], + 6% [78], − 12% [158]	+ 20% [41], + 15% [78]	–	+ 39% [41]
60	− 40% [159], − 30% [107], − 19% [148]	− 26% [107]	+ 5% [160], − 22% [107]	–
70	− 18% [134], − 42% [111], − 30% [113], − 52% [18]	–	− 20% [113], − 30% [68]	− 8% [113]
80	− 28% [163]	− 17% [163]	–	–
Flexural tensile strength				
35	− 45% [88]	–	–	–
40	+ 2% [75], − 31% [41]	+ 10% [75], − 17% [41]	–	+ 8% [75], − 7% [41]
50	− 50% [41]	− 43% [41]	–	− 40% [41]
55	− 45% [41]	− 18% [41]	–	+ 5 [41]
60	− 23% [160]	–	+ 2% [160]	–
70	− 50% [162], − 35% [113]	–	− 22% [113]	–
Splitting tensile strength				
30	− 15% [101]	–	–	− 4% [101]
40	− 30% [49]	− 9% [49]	–	Equal to OPC concrete [49]
50	− 5% [106], − 46% [49]	+ 8% [106], − 38% [49]	+ 12% [106]	− 30% [49]
60	− 25% [59], − 20% [110]	− 15% [69]	− 11% [69], + 3% [110]	–
70	− 48% [112]	–	–	–

ash as cement replacement, respectively. Dragas et al. [157] investigated the time-dependent characteristics of Class C fly ash concrete by partially substituting cement and fine aggregate with fly ash in the range of 50–70% and discovered that the tensile strength of the fly ash concrete increased with time. Singh et al. [170] examined the mechanical characteristics of concrete when mixed with steel fibre and fly ash. Steel fibres and fly ash were the best replacements for cement in concrete for maximal flexural strength at 2% and 10%, respectively. Swaddiwudhipong et al. [171] used a uniaxial tension test on fly ash concrete to see how mineral addition affected the concrete's compressive and tensile characteristics. With 50% cement substitution by fly ash, the 28-day flexural strength of the concrete reduced considerably [90, 172]. Wee et al. [173] observed that the splitting tensile strength of the concrete was affected by various types of mineral admixtures. Alahdal et al. [174] reported a 24% increase in tensile strength with 39% fly ash and rice husk ash in the concrete. Rao and Rao [175] observed the reduction in fly ash concrete's flexural and splitting tensile strength with the increase in temperature. Table 3 represents the mechanical strength of concrete containing fly ash in different percentages and the enhancement or reduction vis a vis conventional concrete as assimilated from various researches.

It is deduced from the above literature that HVFA concrete achieves sufficient tensile strength with time as compared to conventional concrete. However, as the percentage of fly ash replaced increases, the flexural strength of all blends is reduced, particularly for Class F fly ash. Hashmi et al. [176, 177] investigated the age-dependent behaviour of HVFA concrete with low calcium fly ash (Class F fly ash) in a detailed experimental and analytical study.

3.3 Static Modulus of Elasticity

Modulus of elasticity is an essential property in solid mechanics, used in determining and analysing the variations developed in the transformed section of the material. The value of the static elastic modulus varies depending on the grade of concrete and testing methodology. Dragas et al. [157] reported the sharp increase in the value of elastic modulus and compressive strength of HVFA concrete mixtures containing Class C fly ash with respect to concrete age. Khayali and Ahmed [178] observed a 30% and 55% reduction in the 7 days modulus of elasticity of concrete containing 50 and 70% fly ash as cement replacement. Karahan and Atis [179] and Zhang et al. [180] marked a reduction in the elastic modulus of concrete containing Class C fly ash at early ages. Soni and Saini [167] reported a 67% drop in modulus of elasticity of concretes containing 50% fly ash as cement replacement. Yoshitake et al. [169] reported 60%, 14%, 11%, 15%, 20%, and 7% reductions in static modulus of elasticity at the ages of 1, 2, 3, 5, 7, and 28 days concretes using 50% Class F fly ash as cement replacement. With the inclusion of 60% fly ash as cement replacement, Yoon et al. [150] noticed a decrease in elastic modulus of concrete at 28 days. Dinakar et al. [92, 93] observed a reducing modulus of elasticity of concrete when fly ah increased from 50 to 85%. Kurda et al. [181] studied that a low quantity of fly ash did not significantly affect the elastic modulus of concrete. Huang et al. [75] reported that the concrete having Class C fly ash content up to 60% showed good development in the elastic modulus of concrete with respect to concrete age. Siddiqui [41, 145] investigated the static modulus of elasticity of fly ash concrete at various percent replacement of cement by Class F fly ash up to 365 days. It was observed that the elastic modulus of the concrete could be improved with the age of concrete beyond 90 days. Siddiqui and khatib [182] reported the continuous improvement in the modulus of elasticity of fly ash concrete with the age of concrete. The comparison of modulus of elasticity of different percentages of fly ash with respect to the age of concrete is shown in Fig. 10. It is concluded from the previous studies that fly ash in concrete causes an increase in the static modulus of elasticity at later ages. However, a reduction has been observed during early ages.

HVFA concrete achieves sufficient modulus of elasticity, compressive strength and tensile strength with time compared to conventional concrete. When the Portland cement particles react with water, calcium silicate hydrate (C–S–H) and free lime, i.e. calcium hydroxide $Ca(OH)_2$, are formed. However, during the presence of fly ash, this $Ca(OH)_2$ reacts with fly ash particles, and C-S–H compound is formed, which has cementitious properties. The cement utilizes the water for hydration and gains strength during the early days. Once the cement advances considerable strength and the majority of the C–S–H gel is formed, the water goes towards fly ash. That's why fly ash attains strength later than the cement paste.

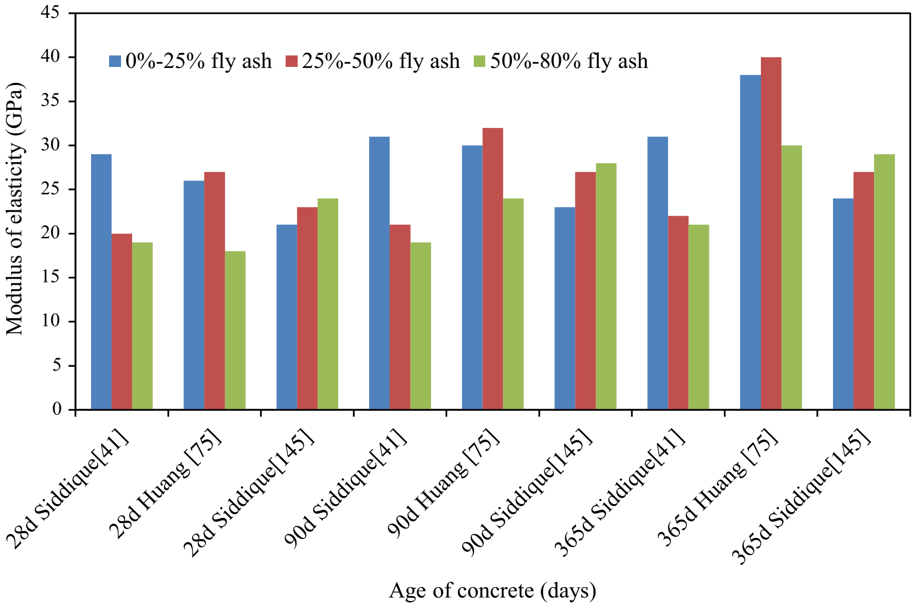


Fig. 10 Comparison of modulus of elasticity of different percentages of fly ash concrete with age [41, 75, 145]

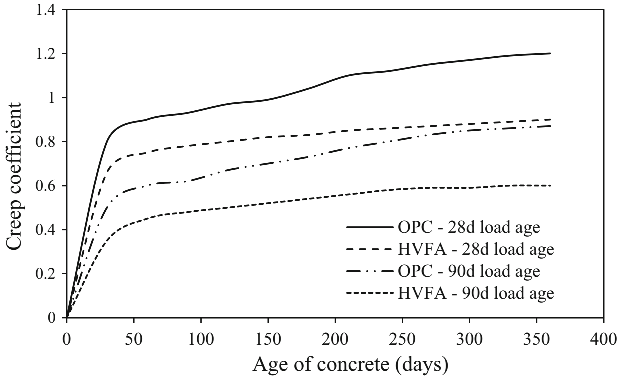


Fig. 11 Variation in creep strain of OPC and fly ash concrete at different age loads [187]

4 Creep and Shrinkage Strain of HVFA Concrete

The deformation rate of a material subject to stress at a constant temperature is called creep strain. The creep strain in the concrete accumulates rapidly in a highly stressed zone, thereby resulting in significant deformation. Creep strains are determined from the results of the application of a constant load (or stress) to a uniaxial concrete specimen held at a constant temperature [183, 184]. The shrinking strain causes fundamental engineering issues, including cracking and prestress loss. The temperature of the atmosphere has a significant impact on shrinkage strain. The total volume change owing to carbonation, temperature change, drying, and autogenous shrinkage should be used to calculate the shrinkage; the loss of water in concrete causes all forms of shrinkage (excluding carbonation shrinkage). Water can either be released into the environment or utilized during the cement hydration process. Shrinkage has a significant impact when massive structural elements such as dams and foundations are exposed to conditions of prevented ultimate strains when one side of the structure is thermally isolated (for example, pavements), and concreting is done in extremely hot climate conditions [185, 186]. Wang et al. [187] reported that fly ash accelerates the creep strain in the concrete and decelerates the shrinkage strain. The differences in the water binder ratio, chemical composition, and loading age affect the creep and shrinkage strain of the fly ash-based concrete. Castel et al. [188] observed that fly ash-based geopolymer concrete observed lesser strain than the OPC concrete at later ages. Arezoumandi and Jeffery [189] reported lower creep and shrinkage strain of HVFA concrete than cement concrete mix by 19% and 13%, respectively. Figures 11 and 12 depict the creep and shrinkage strain variation in OPC and HVFA concrete with the concrete age. It has been observed that shrinkage strains decreased in HVFA concrete in comparison with OPC concrete. The creep strain was also reduced in the case of fly ash concrete, mainly for 90-day load age samples, as shown in the figure.

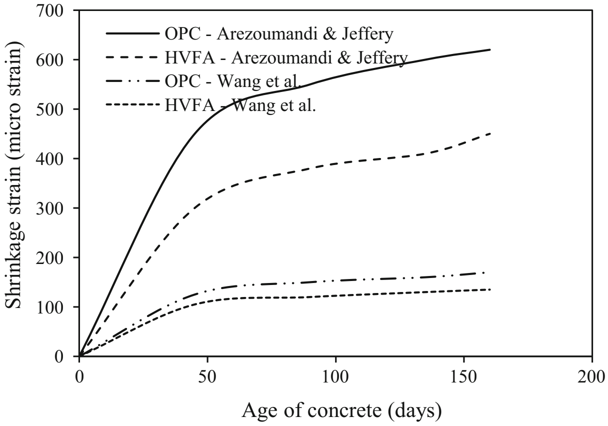


Fig. 12 Variation in shrinkage strain of OPC and fly ash concrete with the age of concrete [187, 189]

5 Non-Destructive Testing Techniques for HVFA Concrete

Non-destructive testing (NDT) is a technique to assess the integrity, characteristics, and quality of materials, components, or systems without destroying them. It is difficult for civil engineers to evaluate the consistency, durability, and strength of concrete without causing damage to it. NDT techniques identify the crack depth on the surface and interior of the concrete, micro-cracks, and its deterioration. Various concrete structures such as bridges, high-rise buildings, tunnels, and structural elements such as beams, slabs, and columns undergo periodic investigation through NDT. Different NDT methods used in the concrete testing are penetration method, rebound hammer method, pull-out test method, ultrasonic pulse velocity method, and radioactive methods. The two most common and widely used NDT methods used to assess the quality of concrete are the rebound hammer and ultrasonic pulse velocity method [190]. The rebound hammer measures the surface hardness of the concrete, whereas a Portable ultrasonic non-destructive digital indicating tester (PUNDIT) employs the ultrasonic pulse velocity to judge the internal flaws, uniformity, and integrity of the concrete.

In the past, several studies on NDT techniques, particularly rebound hammer number (RHN) and ultrasonic pulse velocity (UPV), have been carried out to assess the concrete quality. Sreenivasulu et al. [191] investigated the properties of fly ash-based geopolymer concrete using RHN and UPV. The predicted compressive strength using RHN and UPV was found more than the actual strength of the concrete. Teodoru [192] predicted the strength of concrete using a rebound hammer and observed that only the outer layer of the concrete up to the thickness of 50 mm is adequately assessed by the rebound hammer. Hannachi and Guetteche [193] found that the rebound hammer test is affected by the smoothness of the surface of concrete, internal moisture, rigidity, shape, and size of the specimen. Pucinotti [194] performed NDT on a building with the help of a rebound hammer to assess the quality of concrete structures and reported that the rebound hammer alone is not sufficient to judge the quality of concrete accurately. A new method based on the pulse velocity was developed by Mori et al. [195] to detect the flaws and cracks in the concrete structures. The technique was very effective to judge the concrete structures subjected to impact loading. Polimeno et al. [196] investigated the reinforced concrete (RC) frame affected by seismic action with the help of ultrasonic waves and observed that UPV did not give detailed descriptions of the damage of the structures. Past studies reported that the compressive strength of concrete containing different types of fly ash can be predicted using UPV [197, 198]. Kumar et al. [199] reported the continuous gain in the compressive strength and UPV in the HVFA concrete over a period of 365 days. Anderson and Seals [200] proposed long-term strength measurement of concrete by predicting short-term strength from the pulse velocity. Popovics et al. [201] studied the behaviour of ultrasonic pulses in the concrete containing fly ash and observed that it varies differently across the longitudinal and lateral dimensions of the concrete specimen. Afaneh and Jawed [202] observed that *w*/*c* ratio, moisture content, and curing condition affects UPV in the concrete. The moisture content is inversely proportional to the concrete's pulse velocity and compressive strength. Hashmi et al. [203] reported the significant variation in Class F fly ash concrete strength between the experimental values and the values predicted using RHN. Shaikuthali et al. [204] investigated fly ash concrete's compressive strength using a rebound hammer and observed that the strength obtained using RHN was lower than the actual strength of concrete. Kumar and Rai [205] researched fly ash-based self-compacting concrete on determining the behaviour of UPV in the concrete. The variation in the pulse velocity with the increase in percentages of fly ash is shown in Fig. 13. It has been observed that the pulse velocity in 20–40% fly ash concrete is slightly higher than the other percentages of fly ash in concrete. The rebound numbers and pulse velocity are influenced by several factors like percentage replacement of cement by fly ash, surface condition and moisture content, concrete age, and extent of carbonation of concrete.

The previous literature concludes that various studies have been undertaken using NDT techniques on different types of concrete. However, no detailed investigations on HVFA concrete considering the effect of age-dependent strength have been conducted so far using the NDT techniques such as RHN and UPV.

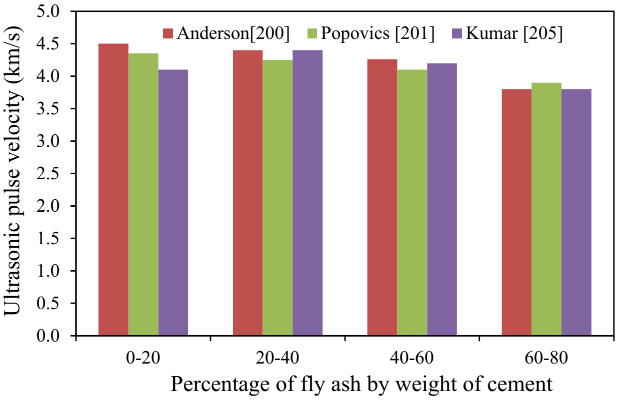


Fig. 13 Comparison of pulse velocity with different percentages of fly ash in concrete [200, 201, 205]

6 Flexural Performance of HVFA Concrete Structural Elements

Increasing the fineness of fly ash enhances the strength of concrete under tension and compression [206, 207]. When incorporated in finely powdered forms, pozzolans usually provide additional mortar strength. Diverse researches have been carried out regarding the flexural performance of the structural elements. Past studies have shown that flexural elements made with fly ash and recycled aggregate have higher deflections and lower cracking moments than conventional concrete [208–213]. The flexural behaviour of RC beams and slabs was also investigated through other innovative methods such as composite steel concrete, precast geopolymer panels, and high-strength concrete [214–217]. The ultimate strength of concrete structures increased with the help of these innovative solutions. Chithambaram and Kumar [218] studied the flexural behaviour of bamboo-based ferrocement slab panels made using fly ash, where the presence of fly ash enhanced the crack resistance behaviour of the slab. Many researchers [219–225] have suggested using fly ash and bamboo as reinforcement in the concrete as a good option for low-cost housing. If a superplasticizer is added to the mix, the problem of more significant instantaneous deflection in HVFA concrete can be solved [226]. According to a research report, the behaviour of fly ash-based concrete under stress is comparable to that of Portland cement concrete [227]. Considering the initial strength of fly ash concrete is attained, HVFA concrete may meet serviceability and strength criteria equivalent to regular concrete. The incorporation of HVFA in the concrete improves the flexural performance and ductility of the concrete structures [228]. It also enhances the tensile strain

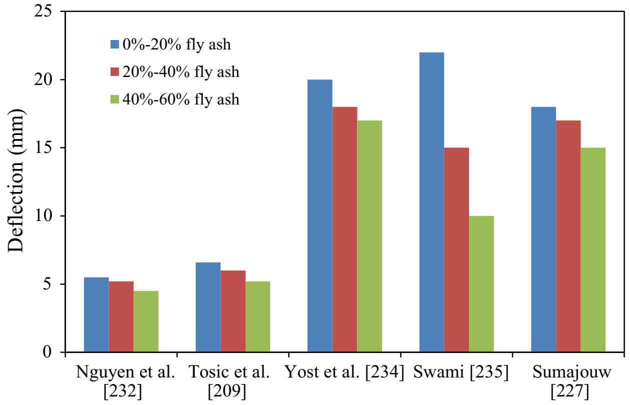


Fig. 14 Deflections in RC beams of fly ash-based concrete at ultimate load

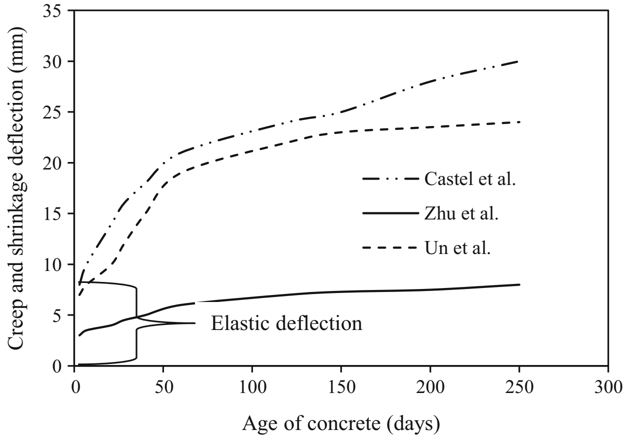


Fig. 15 Time-dependent deflection in RC concrete [188, 236, 237]

capacity and limits fine cracking widths [229]. Several past studies have been carried out to predict the immediate and short-term deflections of the structural members experimentally and analytically and using code provisions [230, 231]. Nguyen et al. [232] investigated the flexural performance of RC beams with fly ash employing both experimental and analytical methods. The observed deflections were compared with the finite element model (FEM) result and were found in good agreement. The deflections in the RC beam of various mixes of fly ash-based concrete at the ultimate load are shown in Fig. 14.

In accordance with the above literature, no detailed analysis of the flexural performance of HVFA concrete structural components has been conducted. Some attempts have been made to examine the behaviour of HVFA concrete, but it is not well established. Hashmi et al. [233] carried out detailed experimental and analytical investigations on the flexural performance of HVFA concrete.

7 Long-Term Deflection of Fly Ash Concrete Structural Elements

Like other materials, concrete also has a tendency to change over time, such as creep and shrinkage. These are the prominent properties of concrete as far as long-term deflection in the design of concrete structures is concerned. When a sustained load is applied on the concrete member, it experiences an immediate deflection at the loading time, followed by a time-dependent deflection over time, as illustrated in Fig. 15. The time-dependent reaction is due to the creep and shrinkage of concrete under the assumption of constant load and temperature. Total deflection in any RC member can be measured as the summation of instantaneous and time-dependent creep and shrinkage deflection. Creep and shrinkage tend to increase gradually over time [238]. Long-term deflection due to creep and shrinkage of the reinforced concrete component is an essential characteristic for structural designers. Deflections in concrete members are difficult to anticipate precisely because of concrete and steel's nonlinear and inelastic characteristics. The effects of mineral admixtures such as fly ash, silica fumes, blast furnace slag, and rice husk ash on the creep characteristics of concrete are considerable which must be assessed realistically.

Tevan [239] investigated the physical and chemical properties, strength, and deflections of sintered fly ash concrete and found it suitable for constructional purposes. The dead weight of the structure (constructed using sintered fly ash) was reduced by 30%. Ghosh and Timusk [240] experimented with fly ash concrete and found that it exhibits significantly lower creep and shrinkage characteristics. OPC concrete slabs experienced more shrinkage, resulting in the formation of cracks due to the evaporation of water from the surface of the concrete [241]. Arezoumandi and Volz [242] tested HVFA concrete beams by replacing 50% and 70% cement with Class C fly ash where similar load–deflection behaviour was received between the two types, i.e. conventional concrete and HVFA concrete. Dragas et al. [157] performed experimental work on HVFA concrete (50–70% Class C fly ash) to determine the creep and shrinkage characteristics for up to 180 days. The superplasticizer was also added to concrete, resulting in the enhanced strength of HVFA concrete thereby leading to a significant reduction in creep and shrinkage compared to conventional concrete.

Laxminarayan et al. [243] conducted an experimental investigation on fly ash-based geopolymer concrete. Seven RC slabs were cast to study its flexural behaviour under the effect of load. The reinforced geopolymer concrete slab behaved similarly like the reinforced cement concrete slab. Soman and Sobha [86] researched the flexural behaviour of HVFA concrete beams. The beams were cast by replacing 50% cement with Class F fly ash. The deflection, cracking behaviour, and load-carrying capability of HVFA concrete beams were all shown to have significantly improved. Shariq et al. [244] investigated the long-term deflection of RC beams containing mineral admixture. The creep deflections were measured up to 150 days under four-point sustained loading. The amount of cement replacement by mineral admixture varied between 20 and 60%. A significant increase in the deflections was noted with the increase in the admixture percentages. However, the contribution of shrinkage in total deflection slightly decreases with the increase in the contents of the admixture. Another study was reported by Shariq et al. [245] on creep and shrinkage characteristics of different grades of concrete. The long-term deflection increased with the reduction in the strength of concrete. However, the creep deflections increased as the percentage of tension reinforcement increased. Tosik et al. [209] did an experiment on the creep and shrinkage characteristics of HVFA concrete beams containing Cass C fly ash. Deflections were recorded for both HVFA concrete beams and conventional concrete beams for a period of up to 450 days under sustained loading. The deflections of HVFA concrete beams were more than the conventional concrete beam.

Wang et al. [246] tested on lightweight aggregate full-scale RC beams containing fly ash to evaluate its long-term behaviour such as deflection, strain and crack width. The long-term behaviour was almost similar to that of a conventional concrete beam. Herath et al. [247] investigated the long-term creep and shrinkage behaviour of HVFA concrete incorporating nano-silica and Class F (low calcium fly ash) up to the period of 450 days. The HVFA concrete observed reduced creep and shrinkage deflection than the deflection predicted by standard design codes. Kristiawan and Nugroho [248] reported a 50–60% reduction in creep when 55–65% cement was replaced by Class F fly ash in HVFA concrete. Yan et al. [249] also reported a decrease in creep deflection with the increase in the percentage of fly ash. From the past studies, it is observed that very few studies have been undertaken in the long-term behaviour of RC structural members containing high volumes of fly ash with and without sustained loading. The creep and shrinkage of fly ash concrete are affected by water-cement ratio, humidity, age of concrete, fly ash content, and admixture in the concrete. The rate of creep is increased with increasing water-cement ratio. Fly ash reduces drying shrinkage by reducing the heat of hydration. Replacing cement with the same amount of fly ash lowers significant heat of hydration of concrete, thereby reducing the shrinkage.

8 Scope for Future Research

Based on the prior studies, it is observed that extensive research has been accomplished on different aspects of HVFA concrete. However, more experimental and analytical investigations are required to determine the durability and long-term behaviour, i.e. creep and shrinkage behaviour of structural or reinforced elements of HVFA concrete such as RC slabs, beams, and columns. Additionally, the effect of nanomaterials such as nano-silica (nano-SiO_2), nano-alumina (nano-Al_2O_3), nano-ferric oxide (nano-Fe_2O_3), nano-titanium oxide (nano-TiO_2), carbon nanotubes (CNTs) and graphene on the age-dependent strengths and creep and shrinkage characteristics of fly ash-based concrete should be investigated. Experimental data and further research related to the long-term behaviour of reinforced HVFA concrete will be needed. Experimental research is always valuable for modelling purposes and analytical solutions. Only modelling and analytical study are insufficient to provide true guidance to the designers and practising engineers. The authors also suggest further experimental tests on different environmental conditions and mix designs for reinforced HVFA concrete structural elements. The research on the HVFA concrete mix design and performance evaluation of structural HVFA concrete needs to be taken to a conclusive state for designing, construction, and sustainable development of concrete industries.

9 Concluding Remarks

The present paper reviewed the fresh and hardened properties of HVFA concrete as well as its mechanical and structural behaviour. The important conclusions derived from the past studies are summarized below.

- Various aspects of HVFA concrete, i.e. workability, durability, heat of hydration, and setting time, have been reviewed. It can be concluded that HVFA concrete has performed favourably in an aggressive environment, particularly in terms of chemical and corrosion resistance compared to OPC concrete.
- The experimental results of the mechanical properties, i.e. elastic modulus, compressive, flexural, and splitting tensile strength of HVFA concrete, have shown significant improvement with respect to the age of concrete due to the pozzolanic action of fly ash particles.
- The strength assessment of HVFA concrete using NDT techniques, i.e. pulse velocity and rebound hammer number has been reviewed. It is observed that UPV and RHN of fly ash-based concrete is lower than the plain concrete as former lacks a rigid structure surface.
- The detailed experimental and analytical investigations have not been carried out regarding the flexural performance, creep and shrinkage characteristics of the HVFA concrete structural elements, i.e. full-scale RC beams and slabs. However, some diverse researches are carried out,

but it is not well established. Past studies have observed that fly ash-based concrete experiences lesser shrinkage strain than OPC concrete, which prevents the formation of cracks during early ages.

- Conclusively, the present review study contains significant updated information pertaining to short- and long-term mechanical as well as structural properties of HVFA concrete while suggesting its effective utilization in concrete industries with considerable potential for future research, which will be instrumental for designers, practising engineers, and researchers.

Declarations

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

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