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REVIEW

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Influence of Fly Ash on the Compressive Strength of Ultrahigh-Performance Concrete: A State-of-the-art Review Towards Sustainability

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Abstract

Fly ash (FA) offers a sustainable alternative to cement in concrete, addressing environmental concerns and enhancing sustainability in construction practices. This substitution contributes to both resource efficiency and reduced carbon footprint. This review study investigated the effect of FA on the compressive strength of ultrahigh-performance concrete (UHPC). No negative effect associated with the increase in FA replacement percentage up to 60% by weight is observed in terms of compressive strength of UHPC without superplasticizer. However, higher replacement percentages are shown to negatively affect the compressive strength. Further investigations should focus on the compressive strength characteristics and limitations associated with elevated levels of FA replacement, i.e. 60–80%. A promising behaviour associated with higher replacement percentages is observed in few studies. Moreover, the superior compressive strengths observed up to 50% FA replacement after a curing period of 90 days underscore the need for a more extensive exploration of longer curing durations. Future studies should focus on investigating the properties of UHPC beyond 90 days, as such information is currently limited.

Keywords Fly ash, UHPC, Superplasticizer, W/b ratio, Curing days, Cement

1 Introduction

Climate change emerges as a pivotal global concern that poses a threat to the sustainability of human society (Hamada et al., 2021). The construction industry accounts for a considerable share of greenhouse gas emissions and significantly contributes to the exacerbation of this critical issue. Presently, the global production of concrete amounts to 2 tons per capita per annum (Abdalla et al., 2022a, 2022b, 2022c; Aïtcin & Mindess, 2011), and it is anticipated that by the end of 2050, this quantity will surge to 18 billion tons (Mehta, 2002). The production and utilization of Portland cement (PC), the fundamental component of concrete, occurs on a massive scale. Notably, China has held the position of the world's largest cement producer since 1985, having manufactured 2.35 billion tons of cement in 2015, representing approximately 50% of the global cement production for that year (L. Shen et al., 2014; Y. Shen et al., 2018). As an example, the energy consumption for producing 1 ton of cement is estimated to range between 3.1 and 5 GJ, concurrently generating approximately 0.73 to 1.0 tons of CO_2 emissions (Hasanbeigi et al., 2012). The cement production ultimately contributes to approximately 7% to 10% of the total global CO_2 emissions (Kim et al., 2013; Liu Zhu 2019; Z. Liu, 2016); Thomas et al. 2021).

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In alignment with the worldwide commitment to sustainable development, professionals have deliberated on technical approaches to ensure the sustainability of concrete construction (Nayak et al., 2022; Shukla et al., 2023; Vilakazi et al., 2022; Thomas et al. 2022; Thomas et al., 2021a, 2021b; Liu et al., 2023; Yang et al., 2019). These strategies encompass efficient material utilization in design, optimization of concrete durability, and incorporation of waste or supplementary cementitious materials (SCMs), such as FA, slag, etc. By adopting these measures, there is a notable advancement towards cleaner production, resulting in the reduction of emissions and waste associated with the manufacturing of materials (Abdalla et al., 2022a, 2022b, 2022c; Abdalla et al., 2022a, 2022b, 2022c; Dam et al., 2016). The widespread adoption of replacing Ordinary Portland Cement (OPC) with FA in concrete is symbolic of the current prevailing shift in construction methodologies (Asa et al., 2020; G. Xu & Shi, 2018). Besides, there has been a lot of interest in using nanomaterials (NMs) to replace long-used components in concrete structures in order to develop concrete with unique functions and superior performance at previously unheard-of levels (Abd El-Aleem & El-Rahman Ragab, 2015; Abd et al. 2014.; S. Abd EI- Aleem et al., 2014). FA is a by-product generated from the combustion of pulverized coal in thermal power plants. The dust collection system (comprise of electrostatic and mechanical systems separators) captures FA as a fine particulate residue from combustion gases, preventing atmospheric discharge (Rashad, 2015; Siddique, 2004). In another aspect, repurposing of waste materials (WMs) such as FA presents a pragmatic solution to waste management issues. The inclusion of FA in concrete endeavors not only provides a purposeful application for the waste material but also alleviates the logistical challenges associated with its disposal (Orozco et al., 2023; Shukla et al., 2023). This underscores the importance of adopting environmentally responsible approaches in waste management practices. Utilizing FA in concrete mitigates power plant waste disposal issues (Erdoğan, 1997). FA has been sourced from power plants. Yazici (2007) collected FA from the Soma power plant in Turkey to use it in his experimental investigations. FA's pozzolanic properties facilitate partial cement replacement, lowering water demand (Ravina & Mehta, 1986) while maintaining workability and enhancing strength. It is worth mentioning that FA has undergone a significant paradigm shift, evolving from a perceived waste material to a valuable by-product with substantial market demand. This transformation is attributed to its versatile uses and benefits in various industries. The present investigation primarily concentrates on exploiting waste FA in the concrete industry, aiming to minimize waste disposal through dump filling to promote sustainable development in the construction sector.

Fly ash is a fine spherical powder that is a byproduct of burning coal gases to produce electricity and is handled as garbage. These tiny earth particles primarily consist of iron, silica, and alumina (Shaw & Sil, 2023). However, improper disposal of FA could negatively impact biological cycles due to the presence of micron-sized particles. Therefore, it should be disposed of in an inexpensive manner (Nadesan & Dinakar, 2017). FA provides acceptable binding and adhesion qualities if it is incorporated with cement due to its chemical makeup. FA is, therefore, referred to as supplemental cementitious material. FA improves workability and initially reduces hydration heat and thermal cracking. It also improves the mechanical properties and durability of concrete, mainly in later stages (Hemalatha & Ramaswamy, 2017). Although FA provides several benefits, there are various restrictions that prevent 100% FA from being used.

China, the United States of America, and India account for over 70% of global coal use (Fig. 1). As to the CEA assessment, 132 thermal plants in India create around 166 million tons of FA yearly (Fig. 2). About 56% of FA is used profitably in various ways as depicted in Fig. 2, with the remaining portion still under consideration. FA is more in demand and of greater interest when used for commercial purposes as a cement substitute material. At the same time, this method can absorb industrial waste and lessen the need for cement clinker. There are certain advantages of using FA as a mineral additive in concrete instead of cement. First, there is a drop in the heat of hydration and an increase in environmental greenness, together with a drop in cost. Second, the addition of FA increases durability. Third, the system has a finer pore structure, improved compactness in the interfacial transition zone, and enhanced workability when FA is present. Several publications concerned with the impact of FA on concrete were evaluated. Evidence demonstrated that in the cases where superplasticizers are not used, the slow pozzolanic response indicated that strength increases with age. Some examples have shown a noticeable increase in early strength (Yu et al., 2017). An experimental investigation on the effects of water–binder ratio,

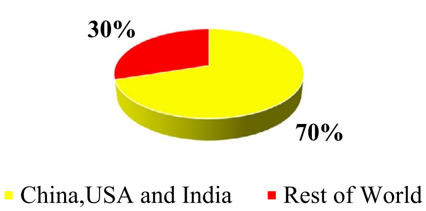

Fig. 1 Consumption of FA (%) by country (Nadesan & Dinakar, 2017)

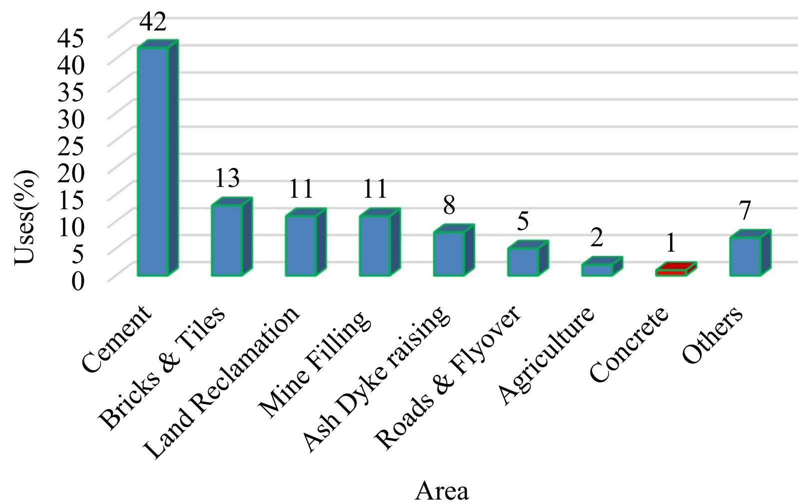

Fig. 2 Percentages of FA uses in various sectors in India (Nadesan & Dinakar, 2017)

FA replacement percentages, and curing period was conducted (Shaw and Sil 2022). Statistical best fit functions were employed for the modelling of these features. This thorough investigation demonstrates that the compressive strength of concrete decreases as the w/b ratio rises. In contrast, maximum strength gaining commences between 7 and 90 days in the case of concrete with FA. Significant strength gaining is observed after 90 days and ultimate strength gaining occurs at 365 days. The highest compressive strength observed is at 20% FA replacement level. Based on the obtained data, some experimental investigations were implemented on the cyclic loading of reinforced concrete (RC) beam–***column joints employing FA–concrete (Shaw & Sil, 2020; Shaw et al., 2022, 2023).

One of the innovative construction materials nowadays is ultrahigh-performance concrete (UHPC), which has far superior qualities than ordinary concrete. According to ASTM C1856-17 (2017), a cementitious mixture falls into the UHPC category if its compressive strength is greater than 120 MPa. However, the ACI committee states that UHPC should have a compressive strength of at least 150 MPa (Meng & Khayat, 2017; Meng et al., 2018; Schmidt & Fehling, 1947). UHPC also exhibits greater durability when compared to traditional concrete (Abuodeh et al., 2020; Attom et al., 2013; Graybeal & Tanesi, 2007; Piérard et al., 2012, 2013; Pyo et al., 2019). It also has remarkable resistance to chemical assault, freeze and thaw, water permeability, and chloride penetration. The fact that UHPC typically contains a significant amount of Portland cement may be its main drawback. In general, UHPC has a cement content that is around three times more by volume than regular concrete (Richard & Cheyrezy, 1995; Rossi, 2013). Despite the extraordinary properties of UHPC, its applications were limited by the extraordinarily high cost of the materials and the intricate production method (Dils et al., 2013).

Recently, according to (Mousavinezhad & Newtson, 2024), pumicite could substitute up to 75% of the FA in the control combination and still produce adequate compressive and flexural strengths for UHPC mixtures. These findings suggest that pumicite can be an adequate substitute to FA in normal strength concrete (NSC) and UHPC combinations. Again, Sun et al. (2024) determined the ideal UHPC mixing ratios with the Waste FA (WFA) and secondary aluminum dross (SAD) assembly unit. In parallel, a number of performance indicators have been acquired, encompassing this kind of UHPC's microscopic, mechanical, electrical, and rheological characteristics. The UHPC's mechanical strength can be computed using its electrical resistance. It was indicated that future solid waste solidification processes will benefit from the new materials and technologies that research will produce.

The goal of this study is to identify the suitable FA replacement percentage that is responsible for improving the compressive strength of UHPC and investigate its direct link to w/b ratio, curing period, and amount of superplasticizer used. A closer look on the related literature reveals that limited research has been conducted to date to extract or generalize the various engineering properties of FA. Therefore, its application is still limited in the construction industry. Additionally, the code of practice does not yet adequately address FA-UHPC or bring forth the limitations regarding its applicability in industry. Thus, this study aims to review the effects of FA on the properties of UHPC in two main categories: with-superplasticizer FA-UHPC and without-superplasticizer

FA-UHPC. An effort was made to accurately measure the engineering characteristics related to FA-UHPC's compressive strength and to establish a helpful correlation between them in order to identify a generalized behavior that affect FA-UHPC with and without superplasticizers.

2 Previous Conducted Reviews on FA-UHPC

Numerous publications have addressed the mechanical behavior of FA-UHPC. Enormous effort has been put into observing how FA affects UHPC, especially with superplasticizer. A thorough analysis of the impact of FA combined with superplasticizer as a substitute for cement on UHPC in terms of compressive strengths has been conducted. Literature suggested that incorporating a supplementary cementitious material which is finer than cement can be used to fill into the voids in concrete since it is effective in enhancing the packing density of the materials. FA represents one such material that has been documented for its utilization in concrete applications. Research indicates that a particle size of 75 µm or less facilitates optimal pozzolanic reactivity (Jin et al., 2000; Shao et al., 2000). Specifically, high-volume FA with a median particle diameter of approximately 24 µm exhibits enhanced reactivity (Azmee et al., 2021a). The particle size distribution of FA exhibits a wide range, spanning from submicron levels (< 1 µm) to over 100 µm, with a median particle diameter typically below 20 µm (Rashad, 2015). The fine FA, with 99% passing through a 45-µm sieve, was utilized in concrete production (Haque & Kayali, 1998a).

The recognition of FA as a pozzolanic ingredient and the understanding of its reaction potentials date back to the early twentieth century. Nevertheless, the first comprehensive study on the utilization of FA in concrete was formally published in the United States in 1937 (McCarthy et al. 2019). According to the studies conducted in the 1980s, it was reported that cement replacement with FA can notably enhance the mechanical and durability properties of the concrete (Montgomery et al., 1981) as FA possesses the capacity to improve the microstructure of the paste (Filho et al., 2013). Some researchers have highlighted that incorporating FA in concrete has the potential to raise packing density and release a portion of the mixing water that would otherwise be trapped in the voids, thereby enhancing the ability of flow (Diederich et al., 2012; Long et al., 2002; Yahia et al., 2005). The latter phenomena were demonstrated through some extensive investigations and corresponding reports (Kwan & Fung, 2011; Olhero & Ferreira, 2004). Zhang et al. (2011) suggested a broad and gap-graded particle size distribution grounded in the close packing theory. Their findings demonstrated that such a particle size distribution could augment packing density and decrease the water requirement in the concrete mixture.

Numerous studies have examined the utilization of FA in UHPC (Du et al., 2022; Jing et al., 2021; Lv et al., 2022). It was reported that the incorporation of 16% FA in UHPC resulted in the highest strength (Ferdosian et al., 2017). Similarly, Chen et al., (2017, 2018) identified that the inclusion of 20% FA yielded the highest flexural strength and compressive strength. Typically, the replacement of 10 to 30% of cement with FA by mass imparts superior properties compared to conventional UHPC. However, in the presence of high calcium FA, an optimal range of 20—40% replacement is recommended for enhanced performance. Luan et al. (2023), Meng et al. (2017), and Meng and Khayat (2017) observed that 10% replacement of cement with FA in UHPC led to improved compressive strength at later stages. This phenomenon can be attributed to the gradual pozzolanic reaction, which, while slow, refines the microstructure over an extended period, ultimately enhancing the concrete compressive strength. Generally, FA demands less water compared to other pozzolanic materials. However, the combination of low water content and a high cement content in UHPC after 28 days resulted in un-hydrated cement grains, inhibiting the dissolution of FA and the pozzolanic reaction between FA and Portlandite (Korpa et al., 2009; J. J. Chen et al., 2017). In the same context, it is found that the replacement of FA in UHPC has the potential to induce the formation of an "elephant skin" under dry conditions. This phenomenon may restrict water escape and mitigate the relative humidity (RH) sensitivity of UHPC (Yalçınkaya & Yazıcı, 2017). Luan et al. (2023) extensively demonstrated that FA displays a positive filling effect in UHPC. Nevertheless, the mechanisms underlying this filling effect, along with the influence of calcium content and the pozzolanic reaction of FA on the enhancement of strength and the development of a dense microstructure in UHPC, remain unidentified (Luan et al., 2023).

According to Haque and Kayali (1998a, 1998b, 1998c), 10% was the maximum amount for cement replacement. Cement replacement in the 400 kg/m^3 series concrete resulted in a very slight increase in drying shrinkage, but there was a minimal decrease in the 500 kg/m^3 series concrete. Rougeau and Borys (2004) demonstrated that the application of ultrafine pozzolanic materials yields additional technical benefits, such as less temperature rise and improved strength enhancement. However, in certain situations, strength development occurs more slowly. Secondary C–S–H gel can be created inside the cement paste by the reaction of ultrafine pozzolanic materials with Portlandite, which is produced during cement clinker hydration. The microstructure of cement paste is more compact thanks to the secondary formation of C-S–H gel. Strength can be significantly increased by reducing the amount of Portlandite. Yazici (2007) elaborated that excessive cement usage increases production costs and can lead to shrinkage issues due to its detrimental impact on the heat of hydration. FA and plasticizer (PS) are good mineral admixtures for concrete because of their pozzolanic properties. Moreover, the durability of concrete may be enhanced by the addition of mineral additives. Nath and Sarker (2011) experimented on the test specimens which were cast, using concrete mixtures that contained FA at levels of 30–40%, of the total binder. The concrete specimens containing FA and control were evaluated for their compressive strength including other mechanical behaviours. The concrete compositions' 28-day compressive strengths ranged from 65 to 85 MPa. When designed for the same 28-day compressive strength of the control concrete, the FA-UHPC samples exhibited less drying shrinkage than the control concrete samples. Alsalman et al., (2017a, 2017b) expressed that when compared to natural sand, the use of FA as a fine material has minimal impact on compressive strength at 28 days of age. Wang et al. (2017) presented that FA microspheres (FAM) can greatly enhance pore structure at later stages. Additionally, FAM can reduce early-age autogenous shrinkage while enhancing concrete's flowability, late-age strength, and permeability to chloride ions. Comparing concrete containing ultrafine FA to concrete containing silica fume, significant decreases in autogenous shrinkage and a higher shrinkage cracking resistance have been reported (Haque & Kayali, 1998a, 1998b, 1998c; Subramaniam et al., 2005; Xie et al. 2002). Compared to 15% silica fume concrete and plain cement concrete, the autogenous shrinkage value of 15% FAM was considerably lower. This might occur because, in a cement slurry system, the hydration rate of FAM is slower than that of cement and silica fume. The early effective water-to-cement ratio increased when part of the cement was replaced with FAM at the same W/B ratio. This reduced the autogenous shrinkage value and the degree of self-desiccation at early ages (Jiang et al., 2014). When making high- and ultra-high-performance concretes, mineral admixtures play a crucial role in filling up the spaces between the bigger cement particles, improving the rheological characteristics, and minimizing cracking caused by heat release during hydration or early age shrinkage (Ghafari et al., 2015; Kodur et al., 2016; Yoo et al., 2014). Owing to their higher cementitious material and high range water lowering admixture contents, UHPCs are prone to significant autogenous and drying shrinkage under standard curing conditions (Tam et al., 2012). The Natural Pozzolona with 60% (NP60) specimen's significant shrinkage strain can be attributed to the NP's marginally larger particle angularity, which raises the percentage of water retention (Shannagt & Yeginobali 1995).

Again, Alsalman et al., (2017a, 2017b) presented that the compressive strengths of the concrete were lower at early ages when the FA content was higher than 20%, but these strengths rose with time. The highest 90-day compressive strength was achieved with a FA percentage of 30%; at all ages, the strengths were least affected by a FA level of 20%. On the other hand, Chen et al., (2017) reported that FA may greatly raise the packing density, improving both flowability and strength performance at the same time. Researchers also reported a thorough analysis of the prospects and present trends in sustainable concrete construction, stressing the significance of implementing eco-friendly methods to lessen the environmental impact of the sector. Permeable concrete, cool concrete, green concrete, additional cementitious ingredients, and utilizing regional resources are investigated as sustainable materials and approach (Nilimaa, 2023).

Several investigations have explored the utilization of high-volume FA (exceeding 50% replacement) in UHPC. Notably, (Azmee et al., 2021) demonstrated that high-volume FA substitution yields beneficial outcomes in reducing cement content in concrete. Recent research has revealed that the incorporation of FA yields enhanced concrete strength when accompanied by a low water/cement ratio (Lam et al., 2000; Wang et al., 2012; Yazici, 2007). Conversely, research conducted by (Azmee et al., 2021; Siddique, 2004) revealed that the incorporation of FA leads to a decrease in early-age concrete strength compared to the control mixture. Hakeem et al., (2022a, 2022b) investigated the effect of replacing natural sand with FA on compressive strength. Their findings revealed that a 60% replacement yielded superior compressive strength compared to 40%. This improvement can be attributed to the FA's pozzolanic reactivity, where smaller FA particles fill gaps between cement grains, enhancing strength. However, a significant decline in compressive strength was observed when FA replacement exceeded 80% and 100% (Hakeem et al., 2022a, 2022b). Azmee et al., (2021) demonstrated that 50% FA replacement reduces compressive strength by 5.6% at 28 days and 10.7% at 90 days, relative to the control mix. Similarly, Wu et al., (2017) observed slightly lower compressive strength reductions (5% at 28 days and 6% at 90 days) with 60% FA replacement. Yazici (2007) observed no significant decline at 60% FA replacement, whereas an 80% replacement resulted in a notable 33% decrease in compressive strength at 28 days. Also, as an admixture, FA increases the compressive strength at early age and develops corrosion preventing characteristics at later stage (Maslehuddin, 1989). Otherwise, investigators have used different superplasticizers in the preparation of UHPC at different percentage. For example, Yazici (2007) has added 4% but Haque and Kayali (1998a, 1998b, 1998c) added 6% of superplasticizers by weight of cementitious material in the mixture. Readers seeking more information on specific superplasticizers are directed to the corresponding references.

Previous research studies have been conducted in mixed form, i.e. FA with other additives. In this paper, only superplasticizer was taken into consideration with FA to measure the effects of both parameters, inclusion and exclusion of superplasticizer in FA-UHPC. It should be noted that this review is concerned only with Class F fly ash. The primary goal of this review paper is to examine how FA, as a cement replacement material, affects the compressive strength of UHPC after compiling the necessary data from various experimental reports and results. To investigate how admixture contributes to the acquisition of different engineering properties in FA-UHPC, the literature review in this investigation is categorized into two main areas: (1) Effects of FA on the compressive strength of UHPC, with or without superplasticizer, while taking into account various properties; and (2) Effects of external parameters such as water–binder ratio, curing days, and level of replacement on the properties of FA-UHPC.

3 Data Analysis and Results

A total of 100 and 120 compressive strength data were collected for with- and without- superplasticizer FA-UHPC, respectively. (Costa et al., 2012; Kou & Xing, 2012; Abd Elrahman & Hillemeier, 2014; Mohseni et al., 2015; Shi et al., 2015; Wang et al., 2016; Martins et al. 2016.; Ferdosian & Camões, 2017; Ferdosian et al. 2017b; Haque & Kayali, 1998a, 1998b, 1998c; Jaturapitakkul et al., 2004; Yazici, 2007; Nath & Sarker, 2011; Alsalman et al., 2017a, 2017b; Alsalman et al., 2017a, 2017b; Chen et al., 2017a; Wang et al., 2017; Wu et al., 2017; Azmee et al., 2021; Hasnat & Ghafoori, 2021; Hakeem et al., 2022a, 2022b). The data was utilized to draw relationships between water to binder (w/b) ratio, FA replacement percentages, dosage of superplasticizer and curing periods on UHPC's compressive strength. The data analysis was segregated into two parts: (1) without-superplasticizer UHPC and (2) with-superplasticizer UHPC, which are discussed intensively in the subsequent sections.

3.1 Without-Superplasticizer UHPC

In this section, the compressive strength of UHPC with different replacement percentages of FA, w/b ratios, and curing periods is collected and analyzed. All data collected in this section is corresponding to an UHPC mix design without superplasticizer.

3.1.1 Water–Binder Ratio

The water–binder (w/b) ratio is the most significant factor for concrete mix design. It is essential for both fresh and hardened concrete since it gives the products mobility, consistency, and a homogenous composition that forms after a chemical reaction or hydration of the constituent parts, which gives the strength for UHPC. The data analysis is conducted from obtained experimental data without superplasticizers and at a curing period of 28 days. The list of data used is presented in Table 1. The objective of this analysis is to study the effect of FA replacement percentages on the compressive strength of UHPC at different w/b ratios. The w/b ratios ranged from 0.1 to 0.35. Experimental data corresponding to a w/b higher than 0.35 is very scarce, as higher w/b ratios lead to as low compressive strength as 70 MPa. Fig 3 shows the relationship between the UHPC compressive strength and percentage of FA used in the mix design, with respect to different w/b ratios. The majority of the collected data is corresponding to a w/b ratio of 0.15 and 0.2, respectively. The trend for these two w/b ratios is nearly constant, indicating that the FA replacement percentage has no negative effect on the compressive strength of UHPC. Moreover, a FA percentage of 60% exhibited almost the same strength as the control specimen (0%) according to Hakeem et al., (2022a, 2022b), and only a 7% decrease in strength according to Wu et al., (2017) data. The trendline for other w/b ratios and for the average is even linearly increasing, indicating a positive effect of the replacement. However, more data points are needed for high w/b ratios (0.25–0.35) to support the trend displayed by the current data. It is noteworthy that the compressive strength data obtained from cube testing are taken directly. However, those which are obtained from cylinder testing are converted to equivalent cube strength (European Committee for Standardization CEN 2004) to maintain consistency in the current database.

The mean compressive strength for each replacement percentage of FA at different water–binder ratios is computed in Table 2 and visualized in Fig. 4. For each w/b ratio, the average compressive strength corresponding to a certain replacement percentage of FA collected from the mentioned references in Table 1 was calculated. Moreover, the percentage of decrease in compressive strength was computed with respect to the mean compressive strength corresponding to 0% FA. A maximum decline of 14.6% in compressive strength of FA-UHPC is noted in Table 2. In fact, most of the FA replacement percentages showed an increase in the mean compressive strength compared to the 0% FA specimens for different w/b ratios. In Fig. 4, it is illustrated that a FA replacement percentage of (20–40) % always resulted in higher compressive strength compared to 0% replacement.

Table 1 Data collected for without-superplasticizer UHPC at different w/b ratio and FA replacement percentages

Reference	FA (%)	w/b	Compressive strength (MPa)
Chen et al., (2017)	0	0.1	88
	0	0.12	135
	0	0.15	122
	0	0.18	110
	0	0.2	95
	0	0.23	88
	0	0.25	80
	0	0.3	70
	20	0.1	125
	20	0.12	155
	20	0.15	145
	20	0.18	135
	20	0.2	130
	20	0.23	115
	20	0.25	110
	20	0.3	110
	40	0.1	125
	40	0.12	135
	40	0.15	130
	40	0.18	120
	40	0.2	110
	40	0.23	105
	40	0.25	100
	40	0.3	100
Wang et al. (2016)	0	0.35	48
	8	0.35	60
	15	0.35	77
	0	0.25	90
	8	0.25	95
	15	0.25	100
Wu et al., (2017)	0	0.2	150
	20	0.2	135
	40	0.2	140
	60	0.2	140
Hasnat and Ghafoori (2021)	0	0.15	134
	10	0.15	129
	30	0.15	126
	40	0.15	119
Hakeem et al., (2022a, 2022b)	0	0.15	161
	40	0.15	150
	60	0.15	158
	80	0.15	143
	100	0.15	130

Table 1 (continued)

Reference	FA (%)	w/b	Compressive strength (MPa)
Ferdosian et al., (2017)	0	0.2	150
	10	0.2	140
	15	0.2	145
	20	0.2	155
	25	0.2	137
	30	0.2	137
	35	0.2	140
	20	0.2	145
	20	0.2	145
	25	0.2	155
	30	0.2	150

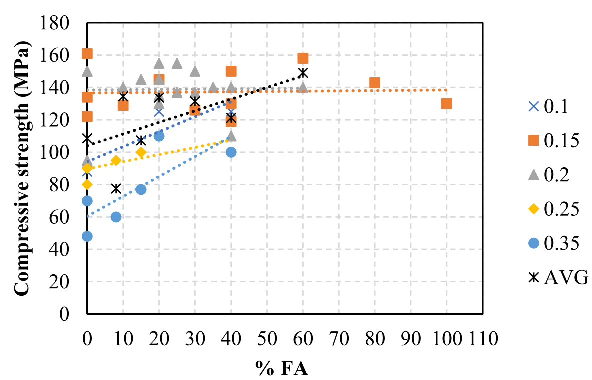

Fig. 3 Compressive strength of without-superplasticizer UHPC versus FA%, for different w/b ratio

Moreover, a replacement percentage of (60–80) % can yield to a satisfactory compressive strength that is comparable to the compressive strength of UHPC without any FA replacement. However, more data points are needed for such higher replacement percentages to verify this assumption.

In certain instances, the compressive strength could not reach 100 MPa. As a result, few explanations are covered in-depth. According to Chen et al., (2018), adding fly ash improves compressive strength, and varying the quantity of fly ash can have varying effects. The increase in FA concentration from 20 to 30% causes a decrease in compressive strength. When 20% FA is added, the compressive strength at 7day and 28day increases by 6.6% and 10.0%, respectively; however, this gain decreases to 3.7% and 6.2% when 30% FA is added. Regarding the impact of FA, a number of studies

Table 2 Mean compressive strength at each w/b ratio for different fly ash replacement percentages

w/b ratio	Fly ash (%)	Mean compressive strength (MPa)	%Decrease with respect to 0% FA
0.1	0	111.5	–
	20	140	– 25.6%
	40	130	– 16.6%
0.15	0	123	
	10	111.5	9.3%
	20	145	– 17.9%
	30	105	14.6%
	40	113	8.1%
	60	158	– 28.5%
	80	143	– 16.3%
	100	130	– 5.7%
0.2	0	125.6	–
	10	140	– 11.5%
	15	145	– 15.4%
	20	131.7	– 4.9%
	25	146	– 16.2%
	30	143.5	– 14.3%
	35	140	– 11.5%
	40	120.8	3.8%
	60	114.5	8.8%
0.25	0	82.2	–
	8	91	– 10.7%
	15	98	– 19.2%
	20	112.5	– 36.9%
	40	102.5	– 24.7%
0.3	0	70	–
	20	110	– 57.1%
	40	100	– 42.9%
0.35	0	60	–
	8	70.3	– 0.4%
	15	81	– 15.7%

revealed that its addition might lower the Ca/Si ratio of hydration products and cause the C-S–H gels of suitable composites to transition quickly to crystalline phases (Hong & Glasser, 2004; Yazici et al., 2008). Also, Wang et al. (2017) gave an idea that from 3 to 28 days, the $Ca(OH)_2$ content of the FA-containing sample increased, suggesting that less $Ca(OH)_2$ was absorbed by FA during this time than was produced by cement hydration. Additionally, it showed that FA had a lower reaction degree. Between 28 and 90 days, there was a considerable drop in the $Ca(OH)_2$ content of the FA-containing sample, suggesting that FA was consuming more $Ca(OH)_2$ than cement hydration was producing during this time. After 90 days, the $Ca(OH)_2$ level of the several samples that contained FA was considerably lower than the sample made of plain cement. From Fig. 5, Wang et al. (2017) narrated that compared to regular fly ash, fly ash microscope (FAM) activity was greater; this was caused by FAM's higher Calcium concentration than regular fly ash in addition to its significantly smaller particle size. Due to the fact that divalent Ca^{2+} can increase the tendency of structural disorder and hence decrease the degree of polymerization in amorphous materials, the damage to the Si–O-Al and Si–O-Si structures was more evident than it would have been with univalent ions (Li et al., 2010; Xu & Deventer, 2000; Yip et al., 2005). Furthermore, Fig. 6 illustrates that nearly all the components in FAM were amorphous, which was advantageous for the rise in FAM activity (Shaikh & Supit, 2015). However, at these early ages, FAM's total reactivity degree was low.

Again, Hasnat and Ghafoori (2021) portrayed compressive strength results, as well as the drying shrinkage for various aggregate-to-cementitious material ratio (V_A/V_{cm}) as a function of curing periods. The compressive strength of the 28-day cured UHPCs ranged from 119 to 149 MPa, 118 to 151 MPa, and 108 to 139 MPa for V_A/V_{cm} of 0.80, 1.0, and 1.20, respectively. The mean drying shrinkages after 120 days were 0.1062, 0.0979, and 0.0896% for V_A/V_{cm} values of 0.80, 1.0, and 1.20, in that order. Fig 7 illustrates the relative performance of the control (C100) UHPC against the binary, ternary, and quaternary UHPCs. As testing time increased, all UHPCs gained vigor from sustained hydration. Binary FA combinations in UHPCs resulted in slower compressive strength growth at early ages compared to the control (C100). The 90-day cured binary UHPCs with FA exhibited comparable or better compressive strength than the control UHPC because to enhanced pozzolanic responsiveness. Nevertheless, UHPC containing silica fume as a partial replacement for Portland cement outperformed the control UHPC in terms of strength improvements throughout all curing ages. Adding reactive fine silica to UHPCs increased their early strength compared to the control UHPC. Similar trends were seen across all cementitious material types and combinations for each V_A/V_{cm} ratio. UHPCs with FA or natural pozzolan had higher long-term compressive strengths, while those with silica fume had higher compressive strengths at a younger age. GGBS-containing UHPCs had marginally lower compressive strengths than control UHPCs at all cement replacement levels. The main hydration process created calcium hydroxide (CH), whereas the secondary pozzolanic reaction produced stronger calcium silicate hydrate (C-SH). This resulted in improved later age strength performance for UHPCs containing FA and natural pozzolans

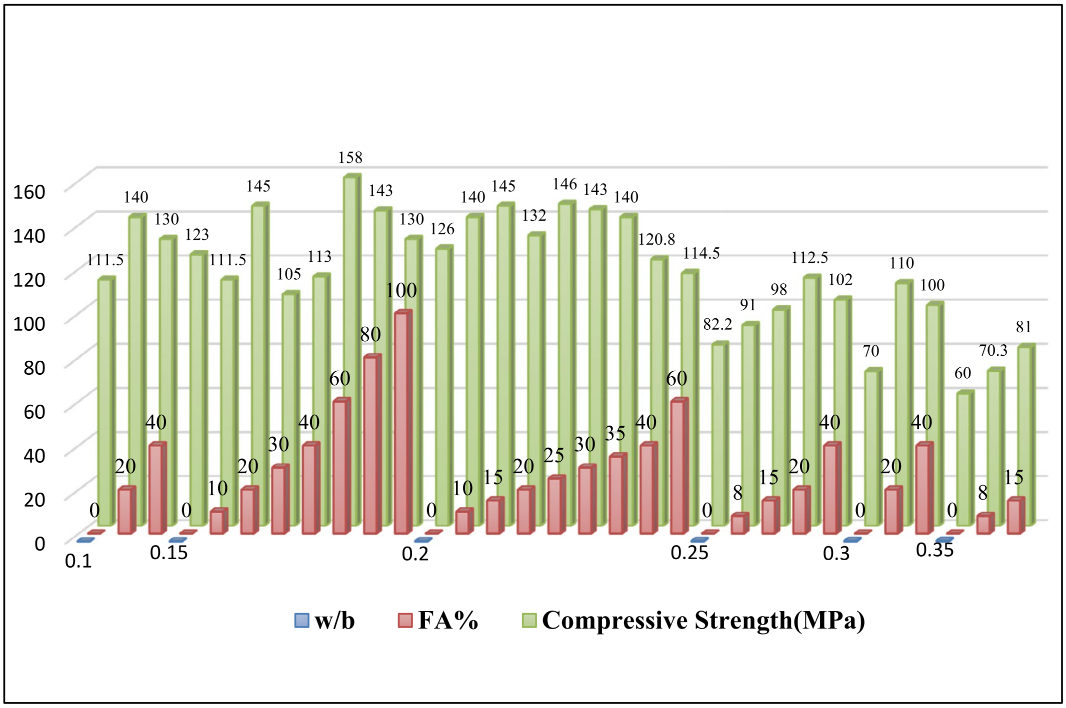

Fig. 4 Compressive strength with respect to w/b and FA%

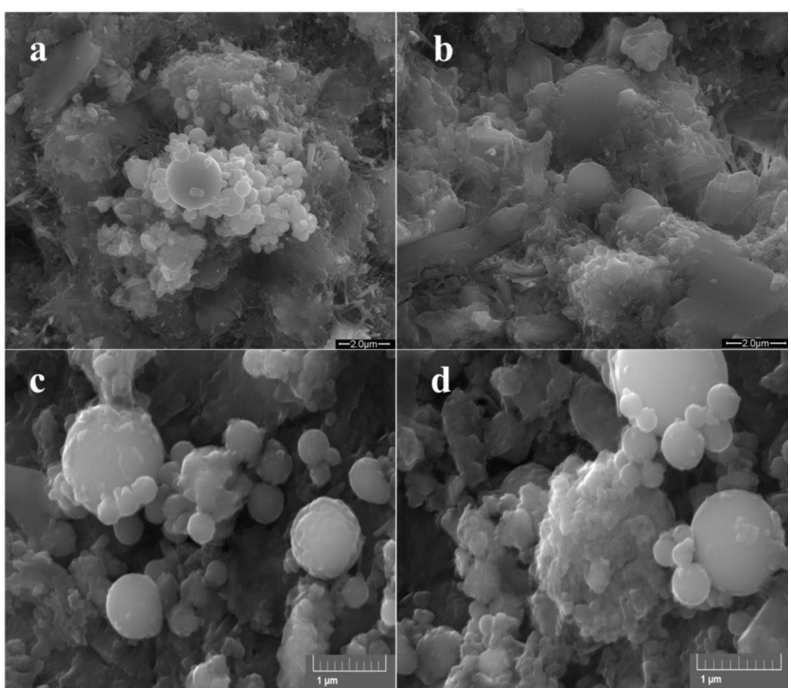

Fig. 5 SEM figures of hardened paste. **a b** at 3 days; **c d** at 90 days (Wang et al., 2017)

(Langan et al. 2002). Adding more FA or natural pozzolan reduced early strength development because to the passivity of the pozzolanic components. The subsequent cementitious reaction between pozzolanic materials and CH produced stronger 90-day cured samples. The use of secondary cementitious elements in

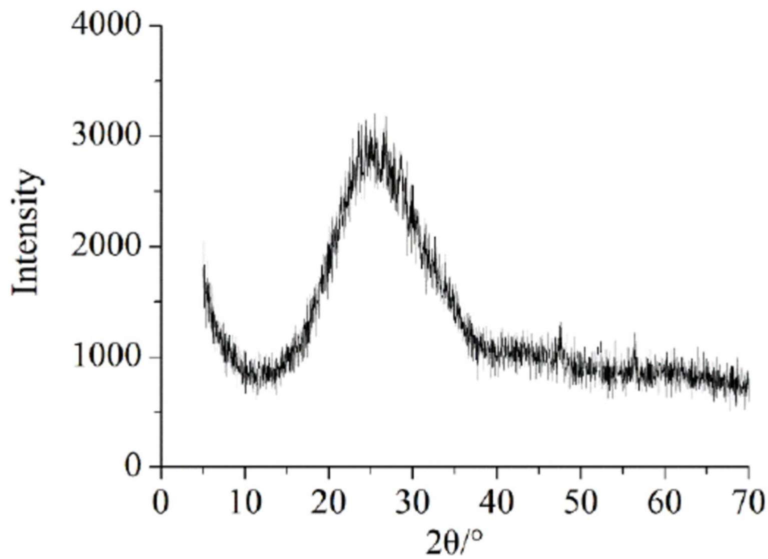

Fig. 6 XRD figure of FAM (Qiang et al. 2017)

UHPC depends on CH formation in the matrix. Without it, these pozzolanic components merely serve as fillers. In general, linear blend UHPCs with FA outperformed slag and natural pozzolan. FA's spherical shape efficiently covered micro deficiencies in the matrix, surpassing irregular GGBS or natural pozzolan shapes (Fig. 8). Asymmetric UHPCs created with FA superior to those prepared with natural pozzolan or GGBS, leading to a bit more strength (Hasnat & Ghafoori, 2021).

On the other hand, (Hakeem et al., 2022a, 2022b) presented the various mixes' average compressive strengths at 3, 7, 14, and 28 days of age in Fig. 9. Following 28 days of curing, compressive strength substantially elevated when compared to previous ages of specimens. The compressive strength of UHPC specimens fluctuated between 125 and 135 MPa at 14 days and 150 to 158 MPa at 28 days of age. Micro silica (MS) replacement levels of Metakaolin (MK), FA, and Natural Pozzolan (NP) led to modestly inferior later age compressive strength compared to the control, with the exception of M0 mix specimens. The FA60 mix, including 60% FA, achieved the highest compressive strength (158 MPa) over 28 days. FA plays a role in improving compressive strength of various mixes, which may be influenced by reduced particle size. This FA is used as a filler material among cement grains because of its pozzolanic reactants.

3.1.2 Curing Period

Utilizing data gathered from previous published literature presented in Table 3, Fig. 10 is plotted. It should be noted that most of the available data in the literature is corresponding to a w/b ratio of 0.2 and 0.15, respectively. Also, for w/b ratios 0.35 and 0.25, the maximum reported replacement percentage of FA was 15%. Fig 5 illustrates the variation in compressive strength as the FA percentage is increased at different curing periods, namely, 3, 7, 28, and 90 days, plotted separately for each w/b ratio. For w/b ratios of 0.3 and 0.25, the compressive strength increases linearly as the FA replacement percentage varies from 0 to 15% at all curing periods. For w/b ratios of 0.2 and 0.15, the FA replacement percentage ranged from 10 to 100% Wt, as shown in Fig. 10c and d. It is noted that the compressive strength of UHPC decreases with the increase in FA replacement percentages at a curing period of 7 days. Nevertheless, the data recorded for a curing period of 28 days showed an almost negligible decline in compressive strength as the replacement percentage increased. For a curing period of 90 days, no change in compressive strength of UHPC is observed as the FA replacement percentage increases. This emphasizes on the fact that the FA matrix gains strength with time.

The relationship between the mean compressive strength and different percentages of FA at different

(See figure on next page.)
Fig. 7 Comparative characteristics of the UHPCs with the control UHPC (C100) at three different aggregate-to-cementitious materials ratios: **a** 0.8 for aggregate-to-cementitious materials; **b** 1.0 for aggregate-to-cement; **c** 1.2 for aggregate-to-cementitious materials (Hasnat & Ghafoori, 2021)

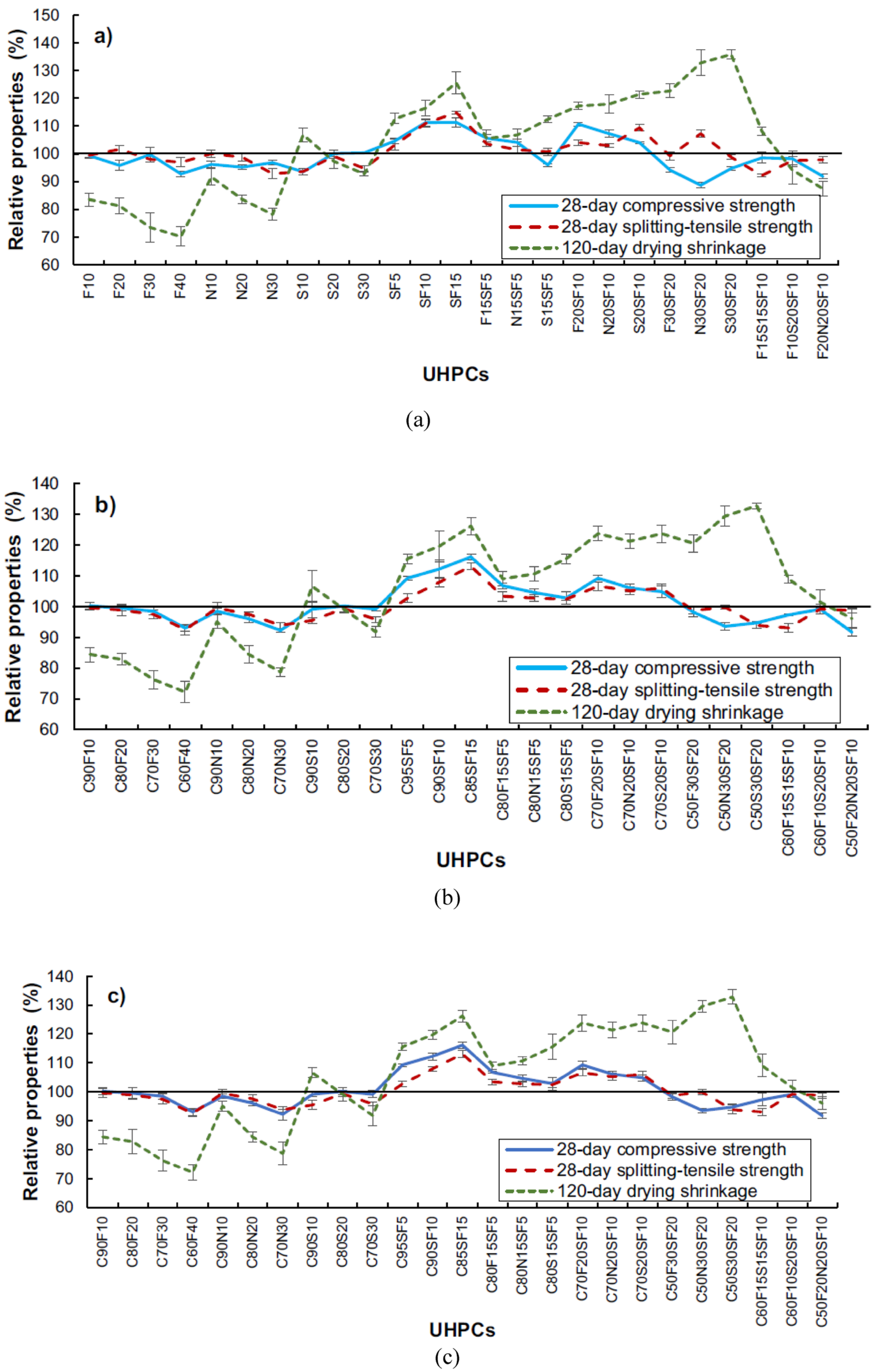

Fig. 7 (See legend on previous page.)

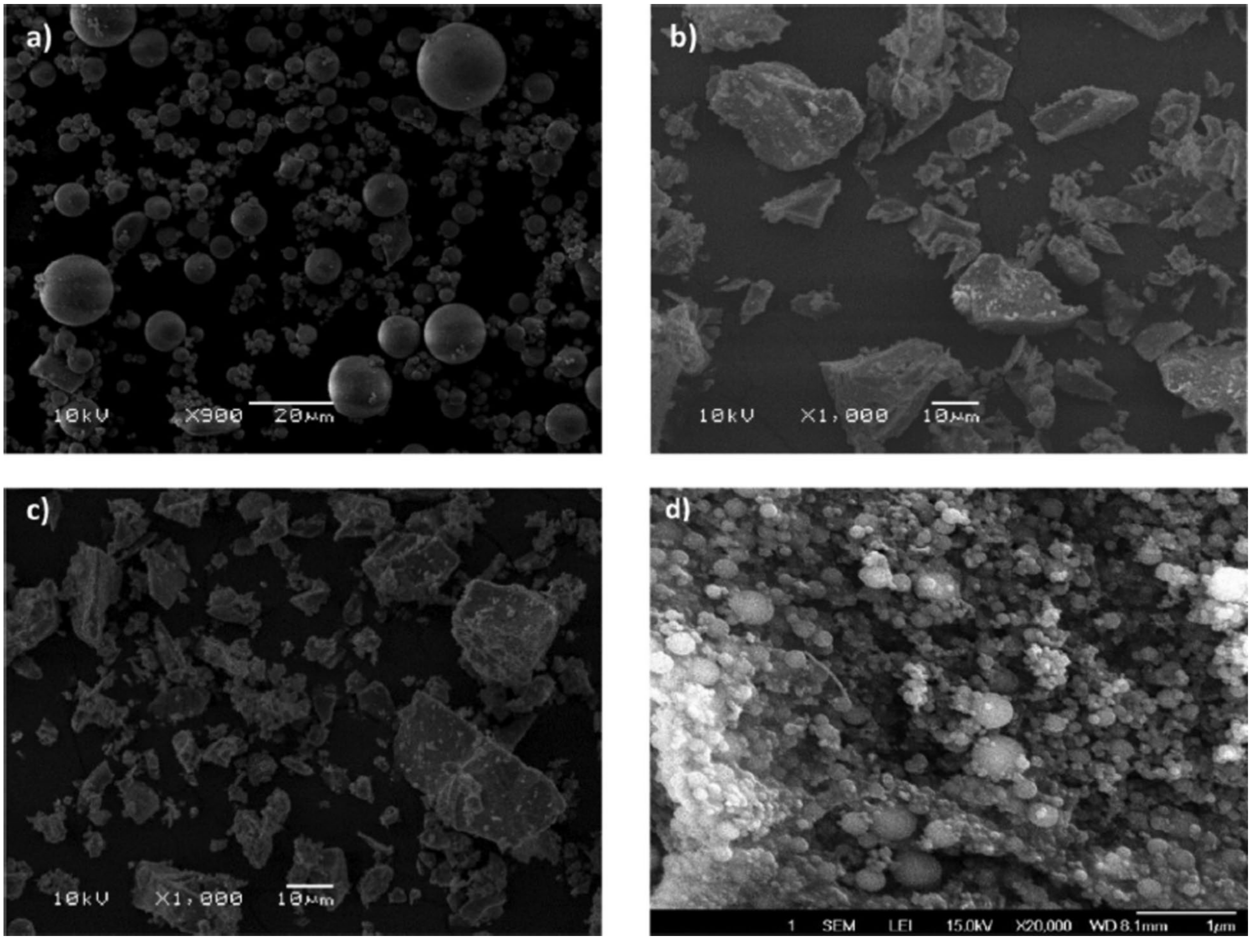

Fig. 8 An image captured by a scanning electron microscope (SEM) of the cementitious materials (**a**) class F FA, **b** natural pozzolan, **c** powdered granulated blast-furnace slag, and (**d**) silica fume (Hasnat & Ghafoori, 2021)

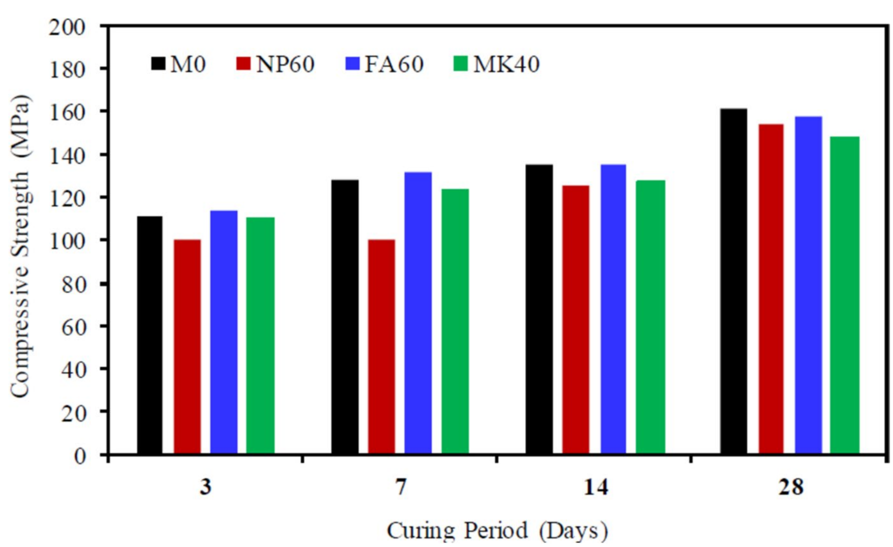

Fig. 9 Compressive strength of UHPC at different ages (Hakeem et al., 2022a, 2022b)

Table 3 Data collected for UHPC without-superplasticizer at different curing periods and FA replacement percentages

Reference	%FA	w/b	Curing period (Days)	Compressive strength (MPa)
Wang et al. (2016)	0	0.35	3	50
	0	0.35	7	62
	0	0.35	28	48
	0	0.35	90	80
	8	0.35	3	46
	8	0.35	7	75
	8	0.35	28	60
	8	0.35	90	100
	15	0.35	3	47
	15	0.35	7	90
	15	0.35	28	77
	15	0.35	90	110
	0	0.25	3	75
	0	0.25	7	70
	0	0.25	28	90
	0	0.25	90	90
	8	0.25	3	85
	8	0.25	7	87
	8	0.25	28	95
	8	0.25	90	97
	15	0.25	3	92
	15	0.25	7	100
	15	0.25	28	100
	15	0.25	90	100
Wu et al., (2017)	0	0.2	3	98
	0	0.2	7	122
	0	0.2	28	150
	0	0.2	90	154
	20	0.2	3	85
	20	0.2	7	105
	20	0.2	28	135
	20	0.2	90	150
	40	0.2	3	85
	40	0.2	7	105
	40	0.2	28	140
	40	0.2	90	165
	60	0.2	3	75
	60	0.2	7	93
	60	0.2	28	140
	60	0.2	90	150
Hasnat and Ghafoori (2021)	0	0.15	1	63
	0	0.15	7	105
	0	0.15	28	134
	0	0.15	90	153
	10	0.15	1	63
	10	0.15	7	102
	10	0.15	28	129
	10	0.15	90	152
	30	0.15	1	51
	30	0.15	7	90
	30	0.15	28	126
	30	0.15	90	153
	40	0.15	1	47
	40	0.15	7	81
	40	0.15	28	119
	40	0.15	90	151

curing durations was established. Table 4 provides the mean values of the compressive strength at corresponding curing periods for different FA replacement percentages, and this relationship is illustrated in Fig. 10. Naturally, higher mean compressive strength is observed with longer curing periods. In general, a percentage replacement of FA in the range of 20 to 35% consistently yields favourable results in terms of mean compressive strength of UHPC. For instance, after 7 days of curing, UHPC with a 20% FA replacement attains the maximum mean compressive strength of 105 MPa. Similarly, after 28 days of curing, UHPC with a 25% FA replacement achieves the highest mean compressive strength at 146 MPa. As mentioned before, the later stage of curing (90 days) exhibits an almost constant variation in compressive strength with respect to the FA replacement percentage, with the highest mean compressive strength associated with a 40% replacement of FA.

3.2 UHPC with Superplasticizer

The purpose of this section is to examine and propose possible correlations between compressive strength and w/b ratios, when superplasticizer FA-UHPC is considered.

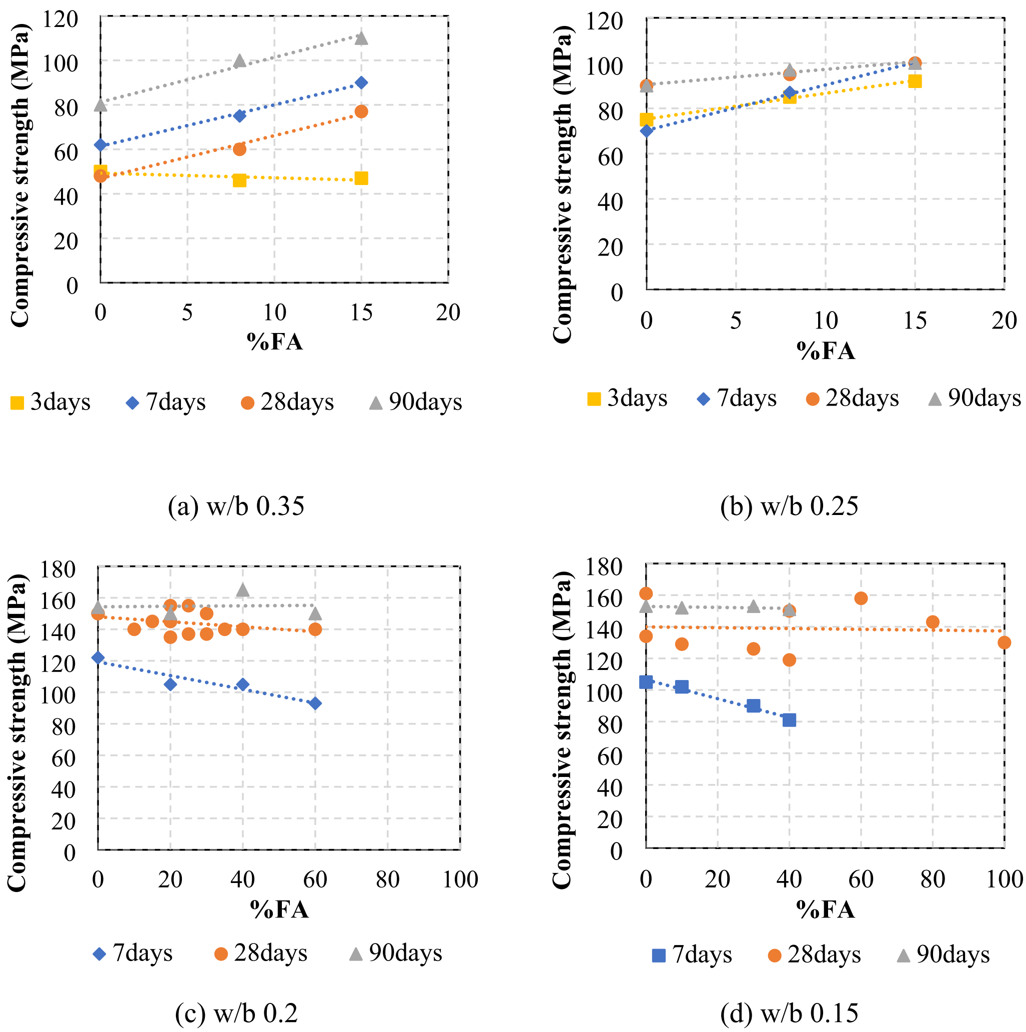

Fig. 10 Effect of FA replacement percentage on the compressive strength of UHPC at different curing periods

Table 4 Mean Compressive strength of UHPC with different FA replacement percentages and at different curing days

FA,%	Mean compressive strength (MPa)				
	1 day	3 days	7 days	28 days	90 days
0	63	74.3	90	108.6	119.5
10	63	–	102	134.5	152
15	–	69.5	95	–	–
20	–	85	105	133.8	150
25	–	–	–	146	–
30	51	–	90	138	153
35	–	–	–	140	–
40	47	85	93	121.3	158
60	–	75	93	145	147

3.2.1 Water–Binder (w/b) Ratio

The data collected for the compressive strength of UHPC with different replacement percentages of FA at different w/b ratios are presented in Table 5. All specimens correspond to a concrete mix design with different dosages of superplasticizer. The compressive strength versus FA replacement percentages is plotted in Fig. 11. A scatter in the data is noticed for all w/b ratios. The average values for each replacement percentage displayed a slight decrease in the compressive strength of UHPC. However, the trend for w/b of 0.2 exhibited a minor increase in the compressive strength. Therefore, more data points are needed for with-superplasticizer UHPC to provide meaningful conclusions on the relationship between FA replacement percentages and UHPC's compressive strength.

The mean compressive strength for each FA replacement percentage and w/b ratio is calculated and

Table 5 Data collected for UHPC with-superplasticizer at different w/b ratio and FA replacement percentages

Reference	FA%	Superplasticizer	w/b	Compressive strength (MPa)
Haque and Kayali (1998a, 1998b, 1998c)	0	6	0.4	77.5
	10	6	0.35	94
	15	6	0.35	73.5
	0	7.5	0.35	92.5
	10	7.5	0.25	111
	15	7.5	0.3	102
Jaturapitakkul et al. (2004)	15	6	0.3	80
	25	5.3	0.3	82
	35	4.3	0.3	80
	50	3.2	0.3	77
Rougeau and Borys. (2004)	25	18	0.2	147
Yazici (2007)	0	45	0.2	117
	20	45	0.3	122
	40	45	0.4	124
	60	45	0.5	117
	80	45	0.65	77
Nath and Sarker (2011)	0	5.11	0.4	65
	30	4.77	0.3	75
	40	4.75	0.3	65
	0	6.77	0.3	85
	40	4.24	0.3	86
Alsalman et al., (2017a, 2017b)	0	30.2	0.2	106.3
	0	30.2	0.2	113.2
	20	30.2	0.2	109.9
	30	30.2	0.2	114.8
	40	30.2	0.2	114.8
	0	34.2	0.2	113.8
	0	34.2	0.2	113.8
	0	34.2	0.2	115.2

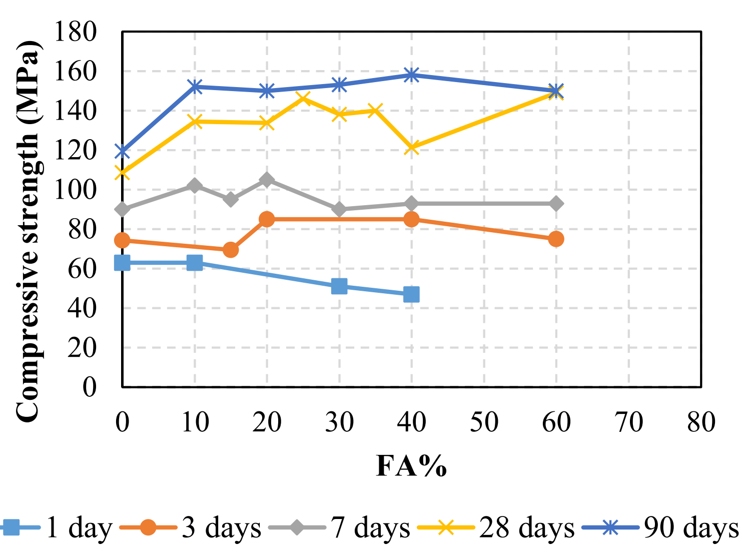

Fig. 11 Mean compressive strength versus FA% at different curing days

Table 6 Mean Compressive strength of UHPC at various w/b ratios and fly ash replacement percentages

w/b	FA%	Mean compressive strength (MPa)	%decrease with respect to 0% FA
0.2	0	107.5	–
	20	98.12	8.7%
	25	148.5	– 38.1%
	30	95.42	11.2%
	40	95.42	11.2%
0.25	10	102.25	–
0.3	0	86.83	15.1%
	15	89.4	12.6%
	20	122	– 19.3%
	25	87.8	14.1%
	30	73.83	27.8%
0.3	35	86.2	–
	40	78.4	9.0%
	50	81.8	5.1%
0.35	0	85.62	0.7%
	10	85.25	–
	15	65.5	23.2%

presented in Table 6. In addition, the percentage decrease in compressive strength with respect to the mean compressive strength of 0% FA is computed. The compressive strength decreased in the range of 0.7 to 27.8%, compared to a maximum decrease of 14.1% portrayed in the previous section for without-superplasticizer UHPC. From Fig. 12, it can be deduced that FA replacement percentage of 25% resulted in an increase in the compressive strength of UHPC compared to a percentage of 0% FA replacement. Fig 13 further illustrates the distribution of compressive strength values corresponding to w/b ratio and FA replacement percentages.

Jaturapitakkul et al. (2004) showed the scanning electron microscopy image of ground coarse FA (FAG) in Fig. 14. Concrete with 15%, 25%, and 35% FAG replacement in lieu of cement developed its strength more quickly than concrete with 50% replacement; at all ages, 25% replacement in place of cement produced the best compressive strength. Using 15–35% content replacements resulted in greater compressive strengths than control concrete at all ages up to 180 days. For example, concrete with 15%, 25%, and 35% FAG substitution had 7-day compressive values of 71.0, 71.2, and 70.8 MPa, respectively, which is approximately 120% of the control concrete. At 28 days, compressive strength increased with curing age for all mixes, ranging from 77.3 MPa in FAG50 to 82.5 MPa in 25% FAG replacement sample. FA's fineness and pozzolanic characteristics provide a packing effect. These features improve concrete strength and density. The results validate Kiattikomol et al. (2001) finding that the fineness of FA significantly impacts the compressive strength of FAG–cement mortar. Furthermore, no significant variation in compressive strength was seen for mortars containing categorized FA and FAG with comparable median particle size.

According to Ferdosian et al., (2017), 4.48 μm FA particles have a stronger and more fluid consistency than 9.3 μm FA particles. The spheroid of the fine particles in FA and their shine surface even after crushing allow for simpler particle sliding amongst each other when mixed on the cement paste (Fig. 15), which is why fluidity is directly dependent on the FA particle size. Since these finer particles can fill in the spaces left by coarser cement particles to create a uniform distribution of

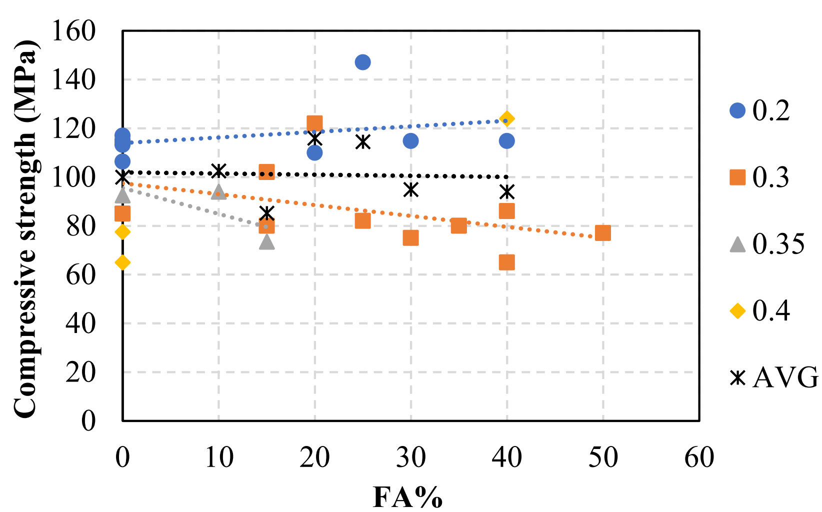

Fig. 12 Compressive strength of with-superplasticizer UHPC versus FA% for different w/b ratio

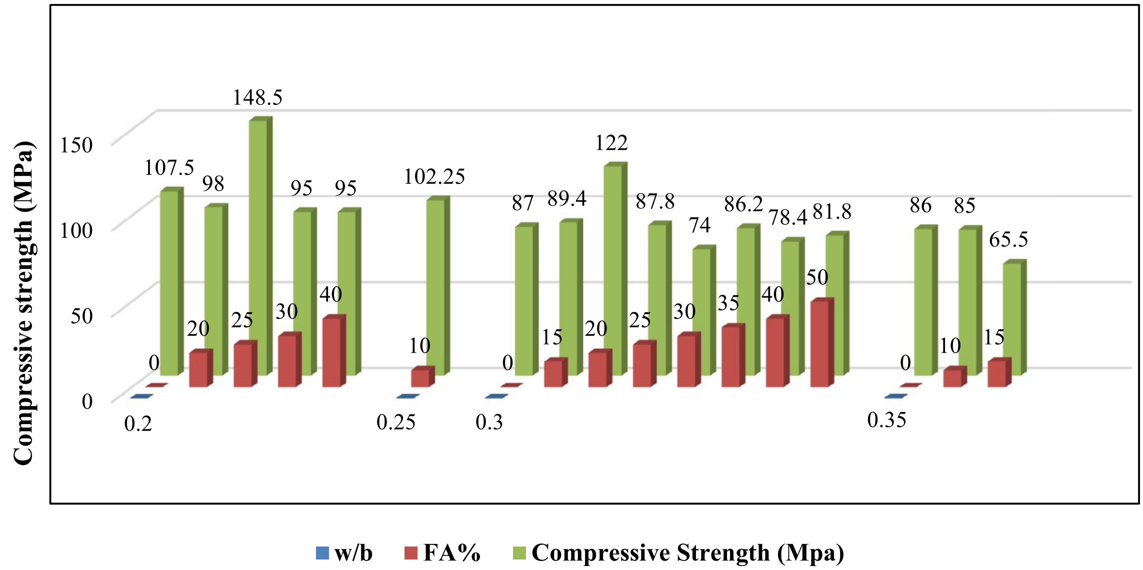

Fig. 13 Compressive strengths of UHPC with respect to FA% and w/b ratios

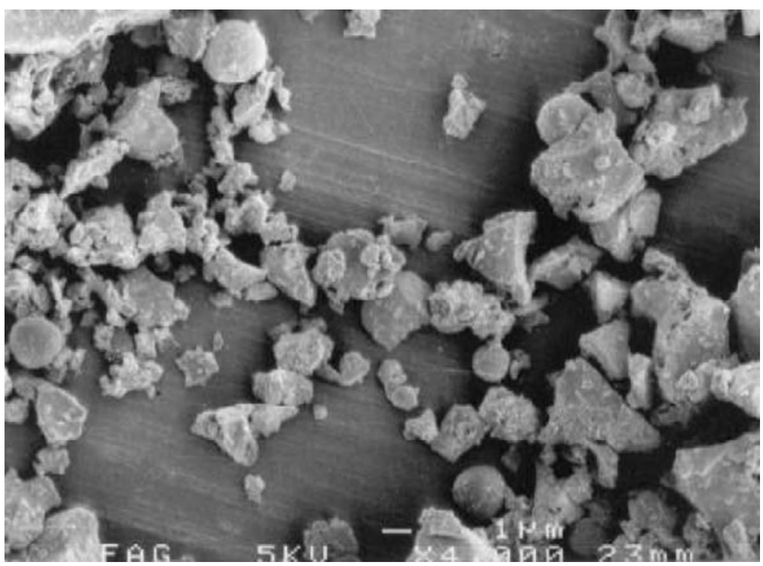

Fig. 14 Scanning electron microscopy image of ground coarse fly ash (FAG) (Jaturapitakkul et al., 2004)

compressive stress, the increase in compressive strength may be related to the finer FA particles' higher activity. These particles may also react with a higher percentage of cement particles in the paste to produce a higher C-S–H development and more substantial packing density.

3.2.2 Curing Period

The effect of curing period and FA replacement percentages on the compressive strength of UHPC with superplasticizer is studied in this section. The data collected for this purpose is listed in Table 7. Also, the compressive strength versus replacement percentages of FA is plotted in Fig. 16, irrespective of the amount of superplasticizer used. A similar trend can be observed in Fig. 16 for the variation of compressive strength of UHPC to the trend of without-superplasticizer UHPC that is shown in Fig. 10 of Sect. 3.1.2. There is an obvious decline in compressive strength at earlier curing periods and the decline fades as the curing period increases to 56 and 90 days. This confirms once again that FA-UHPC gains higher strength with age, regardless of the replacement percentage of FA (Table 8).

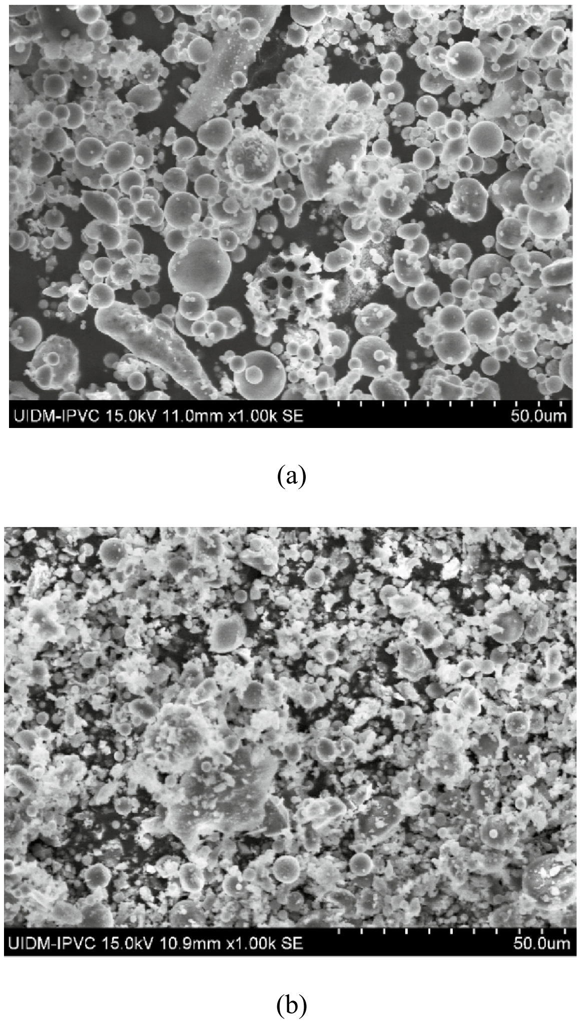

Fig. 15 Low Magnified SEM image of (**a**) 9.3 and (**b**) 4.48 µm FA particles (Ferdosian et al., 2017)

Nath and Sarker, (2011) reported that the FA concretes showed better resistance to the entry of chloride ions at 28 and 180 days. Therefore, it is possible to construct UHPC with reduced permeability by using up to 40% FA into the overall binder. Fig 10 presents the compressive strength versus the FA replacement percentages at different curing days. For all FA replacement percentages in this graph, the compressive strength after 7 days of curing was much lower than it was after other curing times. Due to the use of less FA content, the compressive strengths at 28-day curing intervals were initially higher by 25–30% higher than those at 56-day curing periods. Early in the cementitious system, FA can significantly improve hydration (Wang et al., 2017b). Following that, when FA percentages increased, compressive strengths unexpectedly increased for 56 days during the curing period as opposed to 28 days because of a delayed pozzolanic interaction between FA and superplasticizer that occurred when 30% of FA is used. The compressive strengths at 90 days, however, remained superior for all FA percentages between 0 and 50% because of the noticeably stronger pozzolanic interaction between the FA and superplasticizer. This observation indicates that all curing days, for up to 20–25% of FA, produced improved results. Certain limitations are also discovered in this instance, such as the fact that there is insufficient data to investigate FA replacement rates above 50% in UHPC. In addition, statistics on compressive strength after 90 days of curing are quite uncommon, which means that ideas may still come to fruition later. Moreover, several factors including the type of superplasticizer and its dosage, grade of the concrete, and the w/b ratio, contribute to the UHPC's compressive strength. Wang et al. (2017) demonstrated that FA improved late-age strength even more than silica fume. It is also noteworthy that at 40% FA, the data from tests of 90-day cured compressive strength and 28-day cured compressive strength overlap (Fig. 17).

3.2.3 *Effects of Superplasticizer on FA-UHPC*

The important addition that increases both conventional concrete's and UHPC's compressive strength is the superplasticizer. Table 9 displays the mean compressive strength regardless of the FA replacement percentage. Based on the available data, Fig. 18 is plotted. This figure demonstrated rather clearly how the mean compressive strength increases as superplasticizer concentration increases across the board. This figure made it evident that greater superplasticizer dosages (30–45 kg/m^3) result in stronger compressive strengths, up to roughly 40–60% of FA replacement. However, the quantities were scarce and not widely documented in the literature. This review has also revealed that superplasticizer dosages in the range of 10–30 kg/m^3 have not yet been used. It is noted that the maximum mean compressive strength is 112 MPa. Once the prescribed dosage has been used, superplasticizer effects could be easier to pinpoint and comprehend. Also, not much research has been conducted on the superplasticizer dosage up to 10 kg/m^3 at different FA replacement rates. As a result, no precise understanding of this situation is obtained.

4 Summary and Conclusion

The purpose of this study is to review the effect of various parameters on the compressive strength of UHPC when ordinary Portland cement is replaced by FA. The parameters include FA replacement percentages, water–binder ratios, superplasticizer dosages, and curing period. Several findings have been reached following the analysis of data taken from previous published literature.

Table 7 Data collected for UHPC with-superplasticizer at different curing periods and FA replacement percentages

Reference	FA%	Superplasticizer	w/b	Curing period (Days)	Compressive strength (MPa)
Haque and Kayali (1998a, 1998b, 1998c)	0	6	0.4	7	62
	0	6	0.4	14	70
	0	6	0.4	28	77.5
	10	6	0.35	7	70
	10	6	0.35	14	77.5
	10	6	0.35	28	94
	10	6	0.35	56	99.5
	15	6	0.35	7	58
	15	6	0.35	14	65
	15	6	0.35	28	73.5
	0	7.5	0.35	7	69
	0	7.5	0.35	14	75
	0	7.5	0.35	28	92.5
	0	7.5	0.35	56	106
	10	7.5	0.25	7	84
	10	7.5	0.25	14	93.5
	10	7.5	0.25	28	111
	10	7.5	0.25	56	121.5
	15	7.5	0.3	7	75.5
	15	7.5	0.3	14	89
	15	7.5	0.3	28	102
	15	7.5	0.3	56	113.5
Jaturapitakkul et al. (2004)	15	6	0.3	7	70
	15	6	0.3	28	80
	15	6	0.3	56	90
	15	6	0.3	90	95
	15	6	0.3	180	100
	25	5.3	0.3	7	70
	25	5.3	0.3	28	82
	25	5.3	0.3	56	92
	25	5.3	0.3	90	95
	25	5.3	0.3	180	100
	35	4.3	0.3	7	70
	35	4.3	0.3	28	80
	35	4.3	0.3	56	88
	35	4.3	0.3	90	93
	35	4.3	0.3	180	100
	50	3.2	0.3	7	70
	50	3.2	0.3	28	77
	50	3.2	0.3	56	84
	50	3.2	0.3	90	87
	50	3.2	0.3	180	91
Rougeau and Borys. (2004)	25	18	0.2	28	147
	25	18	0.2	90	150

Table 7 (continued)

Reference	FA%	Superplasticizer	w/b	Curing period (Days)	Compressive strength (MPa)
Yazici (2007)	0	45	0.2	28	117
	20	45	0.3	28	122
	40	45	0.4	28	124
	60	45	0.5	28	117
	80	45	0.65	28	77
Nath and Sarker (2011)	0	5.11	0.4	3	40
	0	5.11	0.4	7	50
	0	5.11	0.4	28	65
	0	5.11	0.4	56	78
	0	5.11	0.4	91	79
	0	5.11	0.4	210	79
	30	4.77	0.3	3	48
	30	4.77	0.3	7	59
	30	4.77	0.3	28	75
	30	4.77	0.3	56	85
	30	4.77	0.3	91	87
	30	4.77	0.3	210	89
	40	4.75	0.3	3	44
	40	4.75	0.3	7	50
	40	4.75	0.3	28	65
	40	4.75	0.3	56	88
	40	4.75	0.3	91	86
	40	4.75	0.3	210	87
	0	6.77	0.3	3	68
	0	6.77	0.3	7	71
	0	6.77	0.3	28	85
	0	6.77	0.3	56	97
	0	6.77	0.3	91	100
	0	6.77	0.3	210	100
	40	4.24	0.3	3	68
	40	4.24	0.3	7	70
	40	4.24	0.3	28	86
	40	4.24	0.3	56	97
	40	4.24	0.3	91	100
Alsalman et al., (2017a, 2017b)	40	4.24	0.3	210	100
	0	30.2	0.2	1	59
	0	30.2	0.2	7	95.7
	0	30.2	0.2	28	106.3
	0	30.2	0.2	56	108.8
	0	30.2	0.2	90	114.1
	0	30.2	0.2	1	70.7
	0	30.2	0.2	7	97.4
	0	30.2	0.2	28	113.2
	0	30.2	0.2	56	113.8
	0	30.2	0.2	90	118.1

Table 7 (continued)

Reference	FA%	Superplasticizer	w/b	Curing period (Days)	Compressive strength (MPa)
	20	30.2	0.2	1	53.7
	20	30.2	0.2	7	99.2
	20	30.2	0.2	28	109.9
	20	30.2	0.2	56	110.3
	20	30.2	0.2	90	117.5
	30	30.2	0.2	1	24.6
	30	30.2	0.2	7	101.2
	30	30.2	0.2	28	114.8
	30	30.2	0.2	56	117.2
	30	30.2	0.2	90	119.3
	40	30.2	0.2	1	24.6
	40	30.2	0.2	7	101.2
	40	30.2	0.2	28	114.8
	40	30.2	0.2	56	117.2
	40	30.2	0.2	90	119.3
	0	34.2	0.2	1	72.8
	0	34.2	0.2	7	102.8
	0	34.2	0.2	28	113.8
	0	34.2	0.2	56	126.2
	0	34.2	0.2	90	139.3
	0	34.2	0.2	1	72.8
	0	34.2	0.2	7	102.8
	0	34.2	0.2	28	113.8
	0	34.2	0.2	56	126.2
	0	34.2	0.2	90	139.3
	0	34.2	0.2	1	73.2
	0	34.2	0.2	7	102.3
	0	34.2	0.2	28	115.2
	0	34.2	0.2	56	129.3
	0	34.2	0.2	90	149.7

- For without-superplasticizer UHPC, most of the reported data in the literature corresponds to a w/b ratio of 0.15 and 0.2. For such w/b ratios, no negative effect associated with the increase in FA replacement percentage up to 60% is observed. For higher w/b ratios (0.25, 0.3), the compressive strength of UHPC was improved with the increase in FA replacement percentage. However, the data corresponding to such w/b ratios is insufficient, and no data is observed for FA replacement percentages beyond 40% for higher w/b ratios.
- Investigations on the effects of FA have shown that it may reduce the Ca/Si ratio of hydration products and accelerate the transition of appropriate composites' C-S–H gels to crystalline phases.
- The collapse to the Si–O-Al and Si–O-Si structures was more pronounced than it would have been with univalent ions, resulting in less reactivity of FA at early curing periods. The divalent Ca^{2+} can boost the tendency of structural unrest and therefore reduce the level of polymerization in transparent substances.
- While UHPCs with silica fume had higher compressive strengths at a younger age, those with FA or nat-

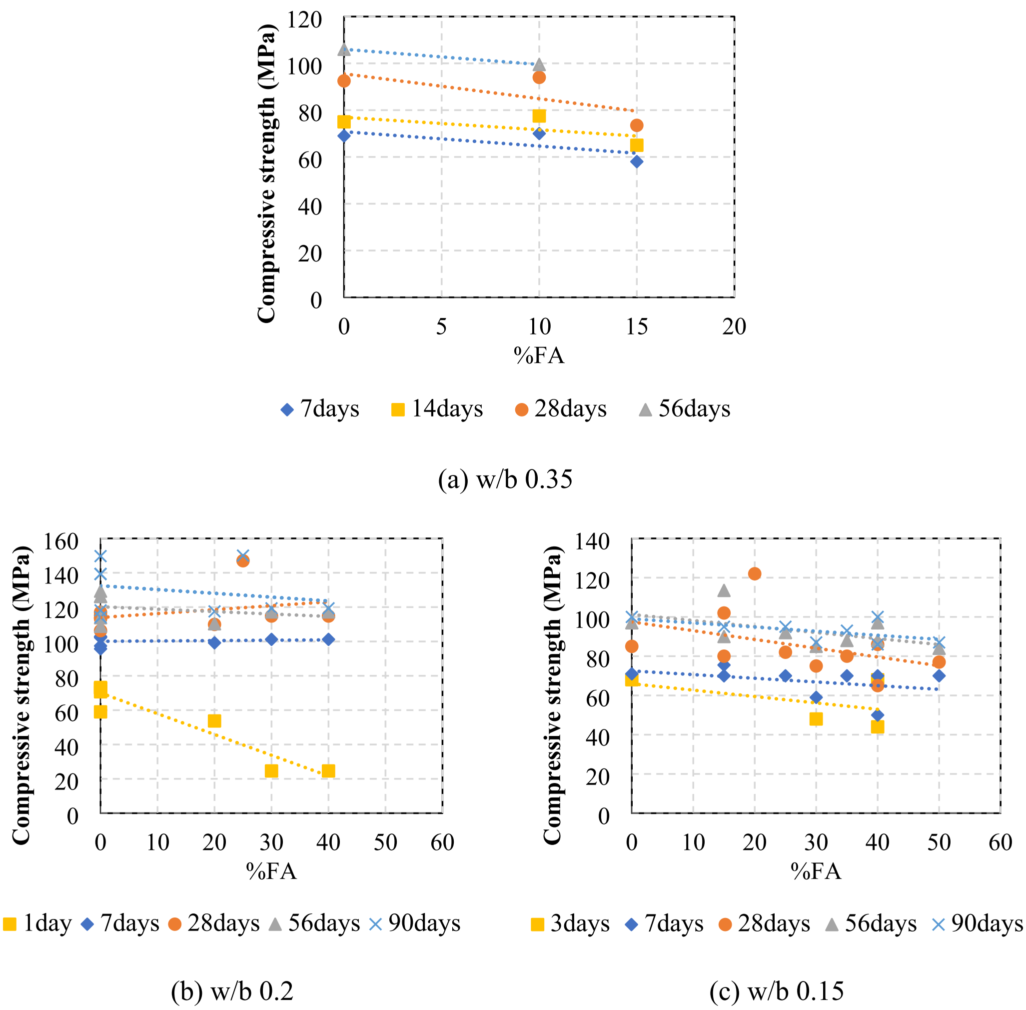

Fig. 16 Effect of FA replacement percentage on the compressive strength of UHPC at different curing periods

Table 8 Mean Compressive strengths of UHPC at various replacement percentages of FA and at different curing days

FA%	Mean compressive strength (MPa)				
	1 day	3 days	7 days	28 days	90 days
0	83.66	100	110.66	120	83.66
20	99.2	116	110.3	117.5	99.2
25	70	114.5	92	122.5	70
30	80.1	95	101.1	103.15	80.1
35	70	80	88	93	70
40	73.73	97.5	100.73	102.65	73.73
50	70	77	84	87	70

ural pozzolan exhibited higher compressive strengths over the long run. At every cement replacement level, the compressive strengths of UHPCs containing GGBS were somewhat lower than those of the control UHPCs.

- The ground coarse FA cement mortar's compressive strength is greatly influenced by the FA's fineness. Moreover, mortars containing classified FA and FAG with comparable median particle sizes did not exhibit any discernible differences in compressive strength.
- Fluidity is directly correlated with FA particle size because the spheroid of the fine particles in FA and their glossy texture following smashing enable smoother particle slips between one other when mixed on the cement paste. In addition, a higher percentage of cement particles in the paste might interact with these FA particles to raise C-S–H development and considerably raise packing density.
- According to few studies, a 60% replacement percentage of FA provided comparable compressive strength to the strength of 0% FA replacement. Nev-

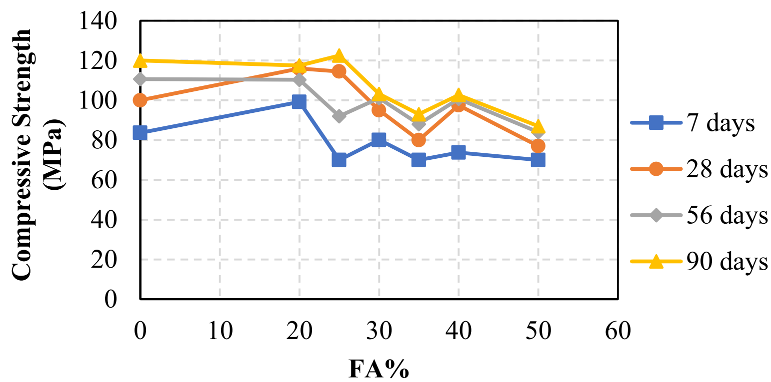

Fig. 17 Mean compressive strength versus FA% at different curing days

Table 9 Mean compressive strength at various FA% replacement and superplasticizer dosages

Superplasticizer dosage (kg/m^3)	%FA	Mean compressive strength (MPa)
3.2	50	81.8
4.24	40	86.83
4.3	35	86.2
4.75	40	70
4.77	30	73.83
5.11	0	65.16
5.3	25	87.8
6	0	69.83
6	10	85.25
6	15	79
6.77	0	86.83
18	25	148.5
30.2	0	99.71
30.2	20	98.12
30.2	30	95.42
30.2	40	95.42
34.2	0	112
45	0	117
45	20	122
45	40	124
45	60	117
45	80	77

ertheless, more data points are needed for such high replacement percentages (60–80%).

- In general, samples that have a FA replacement in the range of 20 to 35% produce satisfactory results for UHPC's compressive strength. The water–binder ratio that ranges from 0.15 and 0.25 when combined with a 20–35% FA replacement provided an optimum compressive strength.
- For UHPC without-superplasticizer and with-superplasticizer, higher curing periods are associated with higher compressive strength and less decline in compressive strength with the increase in FA replacement percentage. For a curing period of 90 days, a minimal decrease in compressive strength is observed when the FA replacement percentage is increased. However, the maximum recorded FA replacement percentage is 50%. Therefore, more data is required for higher replacement percentages.
- For FA-UHPC with superplasticizer, the most consistent compressive strength findings were obtained for a w/b up to 0.2–0.25. Beyond this threshold, no sufficient data is identified in the literature. A decrease in the compressive strength of UHPC is detected with the increase in FA replacement percentage. This might be attributed to the significantly greater pozzolanic interaction between FA and superplasticizer. Nonetheless, the data collected for with-superplasticizer UHPC is limited, and more experimental data is essential to identify an accurate relationship between FA replacement percentage and compressive strength.
- The compressive strengths after 90 days remained superior for all FA percentages between 0 and 50%. Up to 20–25% FA replacement, all curing days showed enhanced results. The tendencies for the 28–90 day and 7–56 day curing periods persisted throughout the FA all-replacement percentages.

5 Future Prospects

This study provided insights into the impact of various parameters on the compressive strength of UHPC, several avenues for future research emerge from the current findings.

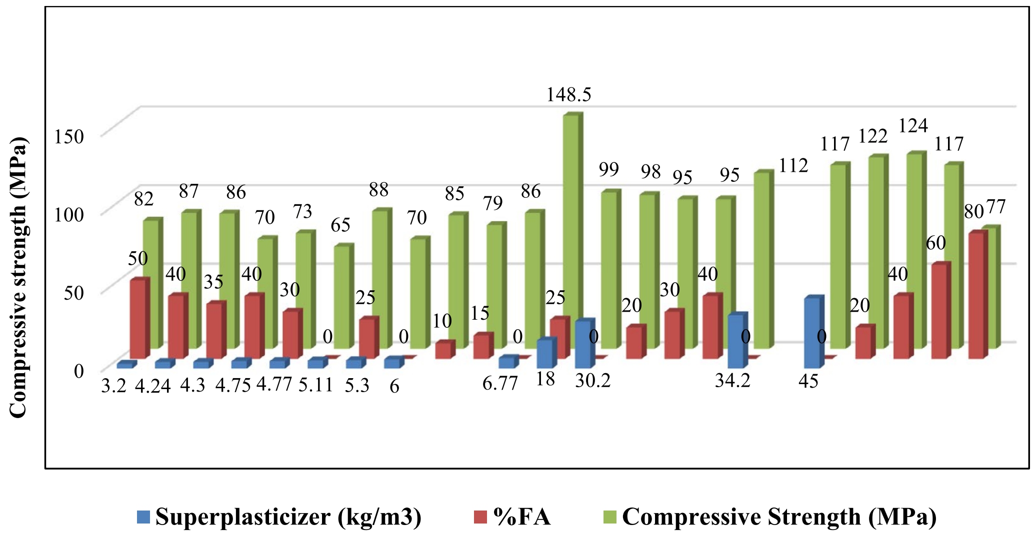

Fig. 18 Compressive Strength versus FA% and superplasticizer dosages

- The study has identified a gap in data for water–binder ratios beyond 0.3 and FA replacement percentages exceeding 40%. Future research should aim to fill this void by exploring the compressive strength trends for UHPC under these conditions.
- Further investigations should focus on gathering additional empirical evidence to confirm the compressive strength characteristics and limitations associated with elevated levels of FA replacement (> 60%).
- The interaction between FA and superplasticizer presents an intriguing aspect affecting compressive strength. Further experimental investigations are necessary to define the intricate relationship between FA replacement percentage and compressive strength in UHPC when combined with superplasticizer.
- The superior compressive strengths observed up to 50% FA replacement after 90 days underscore the need for a more extensive exploration of longer curing durations. Future studies should focus on collecting data on compressive strength beyond 90 days, as such information is currently limited.

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Availability of data and materials
All data applied in this study are available on demand.

Declarations

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Not applicable.

Consent for publication
The authors have given permission for publication.

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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