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Fly ash for sustainable construction: A review of fly ash concrete and its beneficial use case studies

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ABSTRACT

Concrete has a tremendous influence on the environment since the majority of its composition is cement, which is a material that emits high levels of carbon dioxide. It is possible for concrete construction to have a lower impact on the environment if the usage of cement is reduced as much as possible by the addition of mineral admixtures such as fly ash, without sacrificing the durability standards at the same time. The disposal of fly ash, which is produced by power stations that burn coal for fuel, is recognised as one of the most pressing environmental issues. When there is a simultaneous increase in the amount of fly ash and a decline in the capacity of landfills, it is much more difficult to find a solution to this problem. The research on fly ash admixed concrete is analysed and discussed in this publication. There have been many studies conducted on the topic of fly ash concrete and its beneficial effects. In this study, the fresh and hardened properties of fly ash concrete, such as mechanical properties, durability parameters, and microstructural characteristics, are studied. Additionally, the useful application case studies of fly ash concrete published by the American Coal Ash Association are also summarised.

Introduction

Science recognizes the Earth as a closely linked human-environment system and recognizes that our progress as human beings is actually undermined by the means we have chosen to achieve it (The Future is Now: Science for Achieving Sustainable Development, 2017). Sustainable development has become a motif in our contemporary world. The 1987 Brundtland Report defines sustainable development as the development that meets the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland, 1987; G. H., 1987). Energy is the heart of sustainable development goals. According to the International Energy Agency (IEA), worldwide power demand is expected to rise by 5 % in 2021 and 4 % in 2022. Coal-fired power output will grow by over 5 % in 2021, surpassing pre-pandemic levels, after dropping by 4.6 % in 2020. In 2022, it is expected to rise by another 3 %, perhaps reaching an all-time high (IEA Electricity Market Report, 2021). As a result, a large amount of fly ash (FA) will be generated in coal-fired power plants, posing a major concern worldwide. However, a significant amount of FA produced can be used as a cement substitute in concrete (Ilic et al., 2003).

According to IEI (International Energy Agency, 2021), there has been significant growth in CO_2 emissions from the use of energy worldwide, and it is going to be their second-largest annual increase in history. Demand for coal is projected to rise by 60 % in 2021, resulting in a 5 % increase in CO_2 emissions worldwide. As the third-largest industrial energy consumer, the cement industry accounts for roughly 7 % of worldwide CO_2 emissions (Birol, 2018; Ali et al., 2011).

Producing cement is an energy and resource intensive process that results in significant CO_2 emissions during the decomposition of limestone into calcium oxide under high heat created by the combustion of fossil fuels (Ali et al., 2011; Tosti et al., 2018; Latawiec et al., 2018). According to Fayomi et al. (Fayomi et al., 2019) for every 1 kg of cement produced, 0.5–0.9 kg of CO_2 is emitted, resulting in approximately 3.24 billion tonnes of CO_2 emissions every year for the yearly production of

Abbreviations: ASR, alkali-silica reaction; CH, calcium hydroxide; CO_2, carbon dioxide; CS, compressive strength; CSH, calcium- silicate-hydrate; S2S, bi-calcium silicate; C3S, tri-calcium silicate; DEM, dynamic elastic modulus; FA, fly ash; FS, flexural strength; HVFAC, high volume fly ash concrete; ITZ, interfacial transition zone; LS, lime sludge; OPC, Ordinary Portland Cement; MoE, Modulus of elasticity; NWC, normal water curing; RAC, recycled aggregate concrete; RCA, recycled concrete aggregate; SEM, Scanning electron microscopy; SF, silica fume; SP, superplasticizer; STS, Split tensile strength; SWC, seawater curing; TS, Tensile strength; UPV, ultrasonic pulse velocity; XRD, X-ray diffraction analysis.

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3.6 billion tonnes of cement. A significant rise in cement production is anticipated by 2050, making the cement industry responsible for more than 30 % of CO_2 emissions, according to Damineli et al. (Damineli and John, 2012).

Maintaining energy efficiency in kilns, using alternative fuels, and clinker substitution can help reduce CO_2 emissions from the cement industry (Damineli and John, 2012). In the concrete life-cycle assessment, over 85 % of CO_2 emissions are caused by ordinary Portland cement (OPC) production. Reducing OPC and replacing it with a mineral admixture like FA is critical in lowering CO_2 emissions (Kwon, 2016). In this way, we can optimize the use of cement while effectively utilizing FA, which is a byproduct from coal-fired plants.

About 700 million tons of byproducts are produced each year worldwide, of which 70 % is fly ash (FA). FA concrete seems to offer the best solution to reduce cement consumption as large quantities of FA can be obtained for a meager cost (Filho et al., 2013; Ondova et al., 2012). Therefore, an environmentally responsible society must develop low-carbon infrastructure through optimum use of cement and proper use of FA, a waste byproduct that can significantly pollute nearby water resources, the air, and soils otherwise. Rather than being disposed of, FA can be useful both environmentally and economically if it is used in concrete.

This paper explores the usage of FA in concrete and its effect on fresh and hardened concrete. The mechanical and durability properties of the concrete with FA are discussed in the paper. Fracture behavior, the heat of hydration, microstructure, and the effect of type and particle size of FA are also discussed.

Fly ash

Use of FA has become essential for civil engineering because of its economic and environmental benefits (Ravina and Mehta, 1986; Matković, 1990). The amount of cement that FA can replace is restricted by the amount of free lime in the ash. Aside from its chemical composition, the reactivity of FA is determined by its phase composition, the amount of glassy phase present, the burning temperature of coal or lignite, the specific surface area (SSA), etc. (Matković, 1990). FA is a pozzolanic material (Tillman et al., 2012). The term pozzolanic refers to materials that, when exposed to lime and water, will form insoluble cementitious compounds, although they have little or no cementing action when they exist alone (Montgomery et al., 1981).

FA, or pulverised fuel ash, is a byproduct of coal-fired power plants and is used as a mineral additive in cement and concrete. Fig. 1 shows a typical layout of a coal-burning generating station. Pulverized coal is blown into the burning zone of the furnace, where its combustible constituents, mainly carbon, hydrogen, and oxygen, ignite at around 1500 °C (2700°F). Quartz, calcite, gypsum, pyrite, feldspar, clay minerals, and other non-combustible minerals are melted at this temperature and form tiny liquid droplets. The droplets carried by the flue gases from the burning zone are cooled rapidly to form small spherical glassy particles. Mechanical and electrical precipitators or baghouses collect solid particles from flue gases. FA refers to the ash particles that "fly" away from the furnace with the flue gases (Thomas, 2013).

The features of FA are influenced by various factors, including the type of coal used, the burning conditions, the collection mechanism, etc. (McCarthy and Dyer, 2019). The use of FA as a pozzolanic ingredient and its reaction potentials were first recognized in early 1914; however, a substantial study on the use of FA in concrete was first published in 1937 in the United States (McCarthy and Dyer, 2019; Halstead). In the earlier studies in the 1980 s, it was reported that replacing concrete with FA can significantly improve the mechanical and durability properties of concrete (Montgomery et al., 1981) as FA can improve the microstructure of the paste (Filho et al., 2013). Depending on the application, FA properties, specification limits, geographic location, and climate, FA has traditionally been incorporated in concrete at levels ranging from 15 to 25 % by mass of the cementitious material component (Thomas, 2007). It was reported that, in some rare cases, concrete had been successfully placed incorporating up to 80 % FA (Marceau et al., 2002).

The FAs used in concrete are of two types class F and class C according to ASTM. The class F FA is a byproduct of bituminous coal combustion. The iron, silica, and alumina content of class F FA is high, but the calcium content is low. It's a glassy substance that requires either cement or lime to activate. FA from sub-bituminous coal and lignite combustion is classified as class C. It contains more calcium than class F FA. Concrete containing class C FA develops strength much more quickly than concrete containing class F FA (McCarthy and Dyer, 2019; Marceau et al., 2002). The use of FA in concrete is cost-effective, but it also changes the concrete properties in its fresh and hardened states, improving workability, strength, and drying shrinkage. Furthermore, the use of FA in concrete solves the storage and disposal problem of FA, an industrial byproduct (Atiş, 2003).

More than 316 and 188 minerals or mineral groups have been found in the coal and FA; hence the FA possesses a complex nature (Vassilev and Vassileva, 2007). All FA, on the other hand, contains significant levels of silicon dioxide and oxides of aluminum, iron, and calcium. The typical chemical composition of FA from different countries is given in

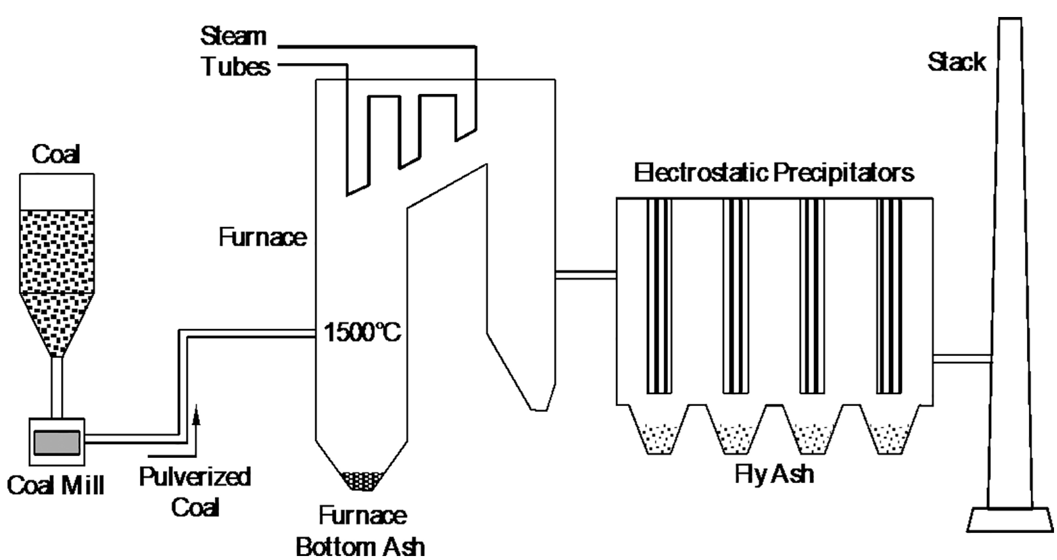

Fig. 1. A schematic diagram of a coal-fired electrical generating station (Thomas, 2013).

Table 1
Typical chemical composition of FA obtained in different countries.

Country	%Chemical Composition											
	S_iO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	MgO	SO_3	TiO_2	Na_2O	P_2O_5	MnO	LOI
Australia	31.1-68.6	17-33	1-27.1	0.1-5.3	0.1-2.9	0-2	0-0.6	1.2-3.7	0-1.5	0-3.9	nd	na
Bangladesh	55	24.7	7.7	6.2	1.1	0.7	1.1	na	na	0.9	0.1	na
Bulgaria	30.1-57.4	12.5-25.4	5.1-21.2	1.5-28.9	0.8-2.8	1.1-2.9	0.4-12.7	0.6-1	0.4-1.9	0.1-0.4	0-0.2	0.8-32.8
Canada	35.5-62.1	12.5-23.2	3-44.7	1.2-13.3	0.5-3.2	0.4-3.1	0.2-7.8	0.4-1	0.1-7.3	0.1-1.5	na	0.3-9.7
China	35.6-57.2	18.8-55	2.3-19.3	1.1-7	0.8-0.9	0.7-4.8	1-2.9	0.2-0.7	0.6-1.3	1.1- 1.5	nd	nd
Denmark	48-65	26-33	3.3-8.3	2.2-7.8	na	na	na	na	1.1-2.8	na	na	3.1-4.9
Europe	28.5-59.7	12.5-35.6	2.6-21.2	0.5-28.9	0.4-4	0.6-3.8	0.1-12.7	0.5-2.6	0.1-1.9	0.1-1.7	0-0.2	0.8-32.8
France	47-51	26-34	6.9-8.8	2.3-3.3	na	1.5-2.2	0.1-0.6	na	2.3-6.4	na	na	0.5-4.5
Germany	20-80	1-19	1-22	2-52	0-2	0.5-11	1-15	0.1- 1	0-2	na	na	0-5
Greece	21-35	10-17.9	4.5-8.4	27.3-45	0.4-1	1.5-3.8	4-8.6	na	0.2-1	na	na	3-7
India	50.2-59.7	14-32.4	2.7-16.6	0.6-9	0.2-4.7	0.1-2.3	na	0.3-2.7	0.2-1.2	na	na	0.5-7.2
Israel	45.6-58.6	24.4-34.5	3-6.7	4.9-9.9	0.1	1.6-2.5	0.6-0.8	1.2-1.9	0-0.1	0.8-1.8	na	6
Italy	41.7-54	25.9-33.4	3-8.8	2-10	0-2.6	0-2.4	na	1-2.6	0-1	0-1.5	0-0.1	1.9-9
Japan	53.9-63	18.2-26.4	4.2-5.7	2-8.1	0.6-2.7	0.9-2.4	03-1.4	0.8-1.2	1.1-2.1	na	na	05-2.1
Korea	50-55.7	24.7-28.7	3.7-7.7	2.6-6.2	l.1	0.7-1.1	0.5-1.1	na	na	0.9	0.1	4.3-4.7
Mexico	59.6	22.8	5.6	3.1	1.3	0.9	0.4	0.9	0.5	0	na	na
Netherlands	45.1-59.7	24.8-28.9	3.3-9	0.5-6.8	0.6-2.9	0.6-3.7	0.2-1.3	0.9-1.8	0.1-1.2	0.1-1.5	0-0.l	2.7-8.1
Northern China	43.7	44	3.5	0.9	0.9	0.4	0.7	1.5	0.3	na	na	10
Poland	32.2-53.3	4-32.2	4.5-8.9	1.2-29.9	0.2-3.3	1.2-5.9	na	0.6-2.2	0.2-1.5	0.1-0.9	0-0.3	0.5-28
Russia	40.5-48.6	23.2-25.9	na	6.9-13.2	1.9-2.6	2.6-4	na	0.5-0.6	1.2-1.5	03-0.4	0.2-0.4	na
South Africa	46.3-67	21.3-27	2.4-4.7	6.4-9.8	0.5-1	1.9-2.7	na	1.2- 1.6	0-1.3	03-0.9	0-0.5	na
Spain	41.5-58.6	17.6-45.4	2.6-16.2	0.3-11.8	0.2-4	0.3-3.2	0.1-2.2	0.5- 1.8	0-1.1	0.1-1.7	0-0.l	1.1-9.7
Spain	41.5-58.6	17.6-35.6	2.6-16	0.8-11.8	0.4-4	0.9-2.5	0.1-2.2	0.5- 1.6	0.2-0.8	0.1-1.7	0-0.l	1.1-5.2
Turkey	37.9-57	20.5-24.3	4.1-10.6	0.2-27.9	0.4-3.5	1-3.2	0.6-4.8	0.6-1.5	0.1-0.6	0.2-0.3	0	0.4-2.7
United States	34.9-58.5	19.1-28.6	3.2-25.5	0.7-22.4	0.9-2.9	0.5-4.8	0.1-2.1	1-1.6	0.2-1.8	0.1-1.3	na	0.2-20.5
Minimum	20.0	1.0	1.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
Maximum	80.0	55.0	44.7	52.0	4.7	11.0	15.0	3.7	7.3	3.9	0.5	32.8

Note: nd = Not detected, na = Not available

Table 1 (Bhatt et al., 2019). The reactivity of FA is influenced by its mineralogical composition and particle characteristics (Bapat, 2001).

Table 2 below summarises global coal FA grain size indices (Bhatt et al., 2019). To avoid differences in concrete properties such as workability, FA must have granulometry or specific surfaces similar to Portland cement (PC) (Wesche, 1991).

Table 3 compares FA production and utilization. China, the world's largest producer of FA, produces 600 million tonnes of FA per year and uses 70 % of it. India produces 226 million tonnes of FA and consumes 83 %.

The classification requirements for FA vary by country. CaO content is the primary consideration in China and in the United States, performance is the primary consideration in Japan, and fineness and loss on ignition are considered in the European standards (Jin et al., 2021). Table 4 lists the different standards for FA in different countries..

The Table 5 lists the properties of FA used in some studies. EN 450-1 specifies that the combined SiO_2, Al_2O_3, and Fe_2O_3 content of FA used in concrete must exceed 70 % by mass (Ohenoja et al., 2019). IS 3812 (Part 1) (Is, 2003) specifies a minimum proportion of SiO_2 plus Al_2O_3 plus Fe2O_3 of 70 and 50 % for siliceous and calcareous pulverised fuel ashes, respectively. Kaewmanee et al. (Kaewmanee et al., 2013) reported that the higher free lime content in FA resulted in earlier setting and higher compressive strength (CS), especially at younger ages. With a high level of free lime in FA, the improvement in CS becomes less significant. A high alkali content in FA can result in an alkali-silica reaction, which causes gel products to swell and exerts expansive pressure within concrete (Jakmunee and Junsomboon, 2011). A high SO_3 level can produce expanding behaviour in concrete, leading to long-term instability (Atiş et al., 2004). A graphical representation of the proportion of SiO_2, Al_2O_3, and Fe_2O_3 in FA used in some studies is given in Fig. 2.

Effect of FA on fresh cement and concrete

Consistency

Consistency of blended cement increases with FA replacement, resulting in higher water demand for the same consistency in comparison to the ordinary Portland cement (OPC), according to Dave et al. (Dave et al., 2016). In this study, replacing 30 % and 50 % of OPC with FA resulted in a 1.6 and 3.1 % increase in standard consistency, respectively, due to the improved fineness of the blended mix. Qafleshi et al. (Qafleshi et al., 2013) reported a 2.6 % increase in consistency with a 30 % replacement of calcareous FA. A similar observation was made by Turgut et al. (Turgut and Demir, 2019) in blended cement with the FA from the precipitator of the thermal station and with the hydrated FA as the FA replacements increased the water demand for the normal consistency. Kishan et al. (Kishan and Prabakar, 2017) examined the consistency as per IS 4031–part 4 (1988) with 20 % FA replacement with or without superplasticizer (SP). This study found that admixed paste consistency is higher than the OPC paste with or without SP. Further consistency of paste with SP was lower than without SP.

The experimental studies by Kizilkanat et al. (Kizilkanat et al., 2016), according to ASTM C187 standards (Astm, 2016) on mortar incorporated with class F FA, showed that up to 35 % of FA replacement the blended cement paste's normal consistency remained the same as that of plain PC paste. Further, they found that the depth of penetration in FA paste was more than the PC paste because FA particles have spherical shapes which reduced the inter-particle frictional force and particles surface to volume ratio, resulting in lower water demand. Other studies also reported a drop in water demand as the FA level increased. Elmrabet et al. (2019) found that the w/c ratio required for normal consistency reduced as FA concentration increased, ascribing to the glassy spherical particles found in FA.

Setting time

The setting time of mineral-admixed pastes normally increases with the percentage of minerals added increases (Brooks et al., 2000); as the fineness of FA increases, the setting time of FA cement decreases. One of the earlier studies on high volume FA concrete (HVFAC) with FA ranging from 35 to 50 % reported an increase in setting time with the increase in FA content. The study examined both C and F class FA and found that the

Table 2
Global coal fly ash grain size indices.

Location of FA origin		FA class	Coefficient of uniformity	Coefficient of curvature	Quality of grading‡	Notes
Country	Plant, city or state					
India	Neyveli	C	3.16	1.04	Poor	Indian coal fly ashes consist predominantly of silt-size fraction with some clay-size fraction.
	Badarpur	F	5.5	2.47	Poor	
	Korba	F	6	1.14	Well	
	Ramagundam	F	1.59	1.09	Poor	
	Vijayawada	F	5.7	0.61	Poor	
	Dadri, New Delhi	F	5.65	0.9	Poor	According to Unified Soil Classification System, both Dadri and Rajghat fly ashes are ML-type soil, non-plastic silt.
	Rajghat, New Delhi	F	4.82	1.01	Poor	
	Orissa	F	4.02	0.94	Poor	Particle size analysis was conducted using a Malvern 3601 particle size analyzer with wet dispersion method in water.
	Orissa	F	3.96	0.93	Poor	
	Orissa	F	4	0.91	Poor	
	Captive Power Plant, Rourkela	F	5.88	1.55	Poor	86.6% fly ash passed 75 mm sieve.
	West Bengal	F	5.44	3.12	Poor	N/A
	Gulbarga, Karnataka	F*	2.14	0.95	Poor	Fly ash particles are of silt size. GFA is finer than the other two. NFA and VFA possess almost similar gradation.
	Neyveli, Tamilnadu	F*	6.67	0.74	Poor	
	Vijayawada, AP	F*	3.67	0.76	Poor	
	Assam	F*	3.67	3.21	Poor	C_c and C_u values were determined according to IndianStandard Procedure.
	Orissa	F*	2.13	1.12	Poor	N/A
	Mouda (Tehsil), Nagpur (Dist.), Maharashtra		7	1.96	Well	Fly ash contained particles the size of silt (68 %), sand (17 %) and clay (5 %).
South Korea	Samchunpo	N/A	18.8	1.05	Well	N/A
	Dong-hae		6	0.91	Poor	
	Seocheon		12.5	1.2	Well	
	Tae-an		13.8	1.08	Well	
Thailand	Mae Moh power plant (classified FA)	F	22	2.39	Well	31% of original fly ash (OFA, median size 19.1 mm) was retained on No. 325 sieve (45 mm). All classified fly ash (CFA median size 6.4 mm) passed through No. 325 sieve.
	Mae Moh Power (original FA)	F	50	1.68	Well	,
	Mae Moh Power Plant	F*	16.67	0.67	Poor	Grain size distribution was obtained from laser particle size analysis
Turkey	Soma thermal plant	C	11.2	1.03	Well	Particle size analyses were performed by sieving and hydrometer method (ASTM D 422, D 1140). Grain size distribution curve indicated predominantly silt-sized uniform material.
	Catalagzi, Zonguldak	F	2.14	0.95	Poor	70 wt% of fly ash consists of particles with dia 2-60 mm (silt size), 25 wt % with diameter 60-200 mm (fine sand size), and the rest medium sand size (200-600 mm).
United States	A. B. Brown Plant, Indiana, USA	F	36.5	2.98	Well	N/A
	Wabash River Plant, Indiana, USA	F	10.3	1.01	Well	
	Delaware	F	4	1.56	Poor	N/A
	Delaware	F	2.8	N/A	Poor	
	New Jersey	F	2.4	N/A	Poor	
	New Jersey	F	3	N/A	Poor	
	Pennsylvania	F	9	1.82	Well	
	Texas	F	28	26.42	Poor	N/A
	Alabama	F	30	18.15	Poor	
	San Juan Mine, New Mexico	F	7.5	1.8	Well	Fly ash was 85.4% finer than a #200 sieve (0.075 mm diameter)

‡According to the classi!cation for sand, N/A = Not available. * Determined based on ASTM.

Table 3
Coal production and utilization in different countries.

Country	**Production (10^6 t/a)**	**Utilisation (10^6 t/a)**	**Utilisation in % of Production**	**Reference**
Australia	6	1.983	33.0	(Staltari, 2020)
China	600	420	70.0	(Ma et al., 2017; Luo et al., 2021)
Russian Federation	22	2.2	10	(Marinina et al., 2021)
South Korea	9.4	8	85.1	(Um and Jeon, Sep. 2021)
Germany				
India	226.13	187.81	83.05	(Mhaske, 2020)
Japan	12	12	100	(Jin et al., 2021)
South Africa				
Poland	3.26	2.82	86.7	(Ściubidło et al., 2019)
USA	30	17.4	58	(Adams, 2019)

Table 4
Different standards for fly ash in different countries.

Country	Designation of standard	Name	Year
Australia	AS/NZS 3582.1	Supplementary cementitious materials for use with Portland and blended cement, part 1: fly ash	2016
	AS 3583: part 1 to 14	Methods of test for supplementary cementitious materials for use with Portland cement	1991 to 2018
Canada	A3000-18	Cementitious materials compendium	2018
India	IS 3812 Part 1	Pulverized fuel ash for use as pozzolana in cement, Cement mortar and concrete	2017
	IS 3812 Part 2	Pulverized fuel ash for use as admixture in cement mortar and concrete	2017
	IS 6491	Methods of sampling fly ash	2021
Japan	JIS A 6201	Fly ash for use in concrete	2015
United Kingdom	BS EN 450-1	Fly ash for concrete. Definition, specifications and conformity criteria	2012
	BS EN 450-2	Fly ash for concrete. Conformity evaluation	2005
	PD CEN/TR 15840	Evaluation of conformity of fly ash for concrete. Guidelines for the application of EN 450-2	2009
USA	ASTM C618	Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete	2019
	C311/C311M	Standard test methods for sampling and testing fly ash or natural pozzolans for use in Portland-cement concrete	2018
USSR	GOST 25818	Fly ash thermal power plants for concrete	2017
Germany	DIN EN 450-1	Fly ash for concrete - Part 1: Definition, specifications and conformity criteria, German version	2012
China	GB/T 1596	Fly ash used for cement and concrete	2017

initial setting time varied from 20 min to 260 min, while the final setting time varied from 60 min to 315 min, depending on the type and amount of FA. As a result of the high sulfate content on the surface of the class C FA particles, the setting time was longer than that for class F FA (Ravina and Mehta, 1986). Dale et al. (Bentz and Ferraris, 2010) also reported that class C FA admixed mixtures had a longer setting time than class F FA in HVFA mixtures. However, according to this study, adding 5 % calcium hydroxide (CH) powder and 5 to 10 % rapid set cement significantly reduced the delay in the setting time of HVFA mixtures. Both initial setting time and final setting time of concrete increased with an increase in the replacement level of class C FA from 10 to 50 % compared to the reference concrete (Mugahed Amran et al., 2020). The decrease of initial and final setting times with an increase in curing temperature had been previously reported by Ozgur et al. (Eren et al., 1995), with the longest setting time observed in FA concrete. In this study, the setting times calculated from the proctor penetration test (ASTM C403) showed that a temperature increase within the range of 6 to 80 °C decreased the setting times of concrete with FA up to 50 % cement replacement. HVFA concrete containing 80 % FA had significantly longer initial and final setting times, ranging from 12 to 14 h and 15 to18 hours, respectively (Huang et al., 2013).

Durán-Herrera et al. (Durán-Herrera et al., 2011) have observed that the setting times increased with a higher water to binder (w/b) ratio and FA content. The increment in the initial setting time was 17.54, 36.84, and 49.12 % at a w/b ratio of 0.5, with 45, 60, and 75 % FA, respectively, whereas it was 23.81, 60.31, and 66.67 % at a w/b ratio of 0.6, compared to the respective control samples. Similarly, the increment in final setting time was 23.6, 35.38 and 52.82 % with 45, 60 and 75 % FA at 0.5 w/b ratio and 39.7, 80.67 and 102.35 % respectively at 0.6 w/b ratio.

At a replacement level of up to 30 %, Yurdakul et al. (Yurdakul et al., 2014) also noted a slight increase in setting time, with a w/b ratio rising from 0.44 to 0.45. It was found that the increase in setting time in the class C FA mixture was greater than that in the class F FA mixture, possibly because of sulfate balance effects, according to the authors. Thus, the study suggests that class C FA can be employed effectively in concrete pavements in hot weather in order to slow the rate of setting.

The experimental results (Choi et al., 2012) showed that due to the packing effect of the finest FA particles in the mortar, the setting time of the mortar decreased as the fineness of the FA particles increased. The study also found that the longer the setting time for the higher FA levels.

The studies carried out by Elmrabet et al. (Elmrabet et al., 2019) on FA cement, with up to 45 % FA replacement, demonstrated that FA delayed the initial and final setting times compared to OPC. This is because FA in an aqueous solution increased the SiO_2 level, which reacted with water to form mono silicic acid saturated solution and developed an endothermic reaction which caused lower hydration of the blended cement.

Snelson et al. (Snelson et al., 2011) examined the effects of increasing the FA percentage from 5 % to 40 % in 5 % increments. In this study, the setting time of blended paste increased as the amount of FA increased, but between 30 % and 40 % FA replacement levels the increase was significantly higher. A similar trend was also observed by (Mounanga et al., 2011; Gesoğlu and Özbay, 2007).

Mounanga et al. (Mounanga et al., 2011) and Gesoĝlu et al. (Gesoğlu and Özbay, 2007) showed that the addition of silica fume (SF) or lime filler with FA as OPC replacement diminished the delay in setting time because the finer particle increases the total surface area and forms monocarbonate at an early age, which stabilizes ettringite indirectly (Bonavetti et al., 2001; Lothenbach et al., 2008).

Density

When the replacement level of FA is increased, the density of hardened concrete decreased. Density reductions of about 1.2, 4.6, and 6.9 % were observed with the incorporation of 20, 40, and 60 % FA in concrete (Mardani-Aghabaglou et al., 2013). FA incorporation had no discernible effect on the density of foam concrete (Gökçe et al., 2019).

According to Bouzoubaa et al. (Bouzoubaâ et al., 2010) the two ASTM class F FA, Lingan (Blaine fineness is 1930 cm^2/g) and Sundance (Blaine fineness is 3310 cm^2/g), behaved differently in the 25, 35, and 45 MPa concretes in terms of the density with their replacement level 20, 35, and 50 % by weight of the total cementitious materials. The Sundance FA concrete had a higher density than the Lingan FA concrete at the same replacement level of FA. However, Jiang and Malhotra (Jiang and Malhotra, 2000) previously had reported a slightly high density in Lingan FA admixed fresh concrete compared to Sundance FA at their 55 % replacement level. This may be attributed to a higher specific gravity of Lingan FA with a higher replacement dosage, as the density of the concrete is a function of specific gravity (Barbhuiya, 2011).

Mukharjee et al. (Mukherjee et al., 2013) found a relatively higher density in OPC concrete without FA, likely due to OPC's higher specific gravity than the FA. The study found that the bulk density decreased as the FA content increased by 40 to 60 %. Baert et al. (Baert et al., 2008) also reported a decrease in density of the concrete as FA content increased from 10 to 60 %. According to their study, the density was decreased by 3.27 % when the FA replacement increased from 10 to 60 %. Sua-iam and Makul (Sua-Iam and Makul, 2014) found that the fresh density of the concrete was dropped by 8.35 % when 60 % FA replaced the cement.

According to Bicer (Bicer, 2018) when the FA of various grain size groups, namely un-sieved, greater than 75 μm, 45–75 μm, and less than 45 μm were used as fine aggregate in mortar, the dry density of the samples decreased as FA content increased from 10 to 90 % as seen in Fig. 3. The samples with FA of larger grains had the lowest density after

Table 5
Composition of FA used in some studies.

Reference	SiO_2	Al_2O_3	Fe_2O_3.	SiO_2 + Al_2O_3 + Fe_2O_3	Na_2O (Alkali)	CaO	SO_3	TiO_2	MgO	K_2O	LOI	Fineness m^2/kg	Sp. gravity
Mugahed Amran et al. (Mugahed Amran et al., 2020)	53.8	26.72	5.2	84.8	0.6	5.7	1.5	1.4	2.3	0.7	1.85	365.2	2.51
Saha (Saha, 2018)	76.34	14.72	3.69	94.75	0.19	0.6	0.11	0.61	0.54	0.96	0.53	430	–
Shaikh and Supit (Shaikh and Supit, 2015)	51.8	26.4	13.2	91.4	0.31	1.61	0.21	1.44	1.17	0.68	0.5	–	2.6
	73.4	17.7	4.4	95.5	0.11	0.9	0.2	0.7	0.6	1.03	0.6	251	2.0–2.55
Jena and Panda (Jena and Panda, 2018)	58.13	31	4.1	93.23	0.05	0.6	0.12	1.63	0.1	0.9	0.29	333	2.12
Praveen Kumar and Ravi Prasad (Praveen Kumar and Ravi Prasad, 2019)	63.13	24.93	4.18	92.24	–	4.32	–	–	1.38	–	2.06	318	2.12
Termkhajornkit et al. (Termkhajornkit et al., 2009)	59.9	29.6	4.8	94.3	–	1.3	–	–	0.6	0.7	0.9	376	2.29
Hassan et al. (Hassan et al., 2000)	49.9	26.5	8.1	84.5	1.5	1.7	0.9	–	1.3	3.6	3.8	–	–
Rao et al. (Rao et al., 2016)	62.84	23.94	4.74	91.52	0.4	3.43	0.77	–	0.97	0.71	0.73	359	2.5
Islam et al. (Islam et al., 2018)	51.49	31.6	2.8	85.89	0.18	0.65	0.19	–	0.28	–	4.2	–	–
Xu et al. (Xu et al., 2020)	51.8	30.5	5.6	87.9	–	8.1	1.2	–	0.9	–	1	380	2.68
	50.5	32.9	6.2	89.6	–	5.6	1.4	–	0.6	–	1.9	310	2.58
Yazici and Arel (Yazici and Arel, 2012)	45.98	23.55	4.91	74.44	0.24	18.67	1.47	–	1.54	1.8	2.31	231.5	2.21
	45.98	23.55	4.91	74.44	0.24	18.67	1.47	–	1.54	1.8	2.31	384.9	2.45
	45.98	23.55	4.91	74.44	0.24	18.67	1.47		1.54	1.8	2.31	523.9	2.52
Bicer (Bicer, 2018)	51.25	26.15	5.29	82.69	0.67	7.85	0.23	0.83	1.66	1.3	3.32	–	2.03, 1.94, 2.29, 2.42
Gesoğlu et al. (Gesoğlu et al., 2009)	56.2	20.17	6.69	83.06	0.58	4.24	0.49	–	1.92	1.89	1.78	–	2.25
Turk et al. (Turk et al., 2013)	58.82	19.65	10.67	89.14	–	2.18	0.48	–	3.92	–	0.91	287	2.08
Khatib (Khatib, 2008)	50.5	24.7	7.4	82.6	0.8	2.6	0.8	–	1.5	3	–	381.2	–
Sadrmomtazi (Sadrmomtazi et al., 2018)	59.3	23.4	4.8	87.5	3·2	8·6	0·1	–	0·6	–	–	356	2·54
Siddique (Siddique, 2004)	57.3	27.1	5.4	89.8	0.4	6.1	1.4	1.3	2	0.6	0.8	415	–
Fan et al. (Fan et al., 2019)	62.81	21.02	11.63	95.46	2.23	4.25	–	1.35	1.7	2.06	2.11	–	–
Liu and Presuel Moreno (Liu and Presuel-Moreno, 2014)	24.07	27.75	6.67	58.49	0.07	2.11	0.19	–	0.96	2.28	–	–	–
Lam et al. (Lam et al., 2000)	56.8	28.2	5.3	90.3	0.14	<3	0.7	–	5.2	–	3.9	–	–
R.Siddique (Siddique, 2004)	55.3	25.70	5.3	86.3	0.4	5.6	1.4	1.3	2.1	0.6	1.9	386	2.72
Soni and Jasbir Saini (Soni and Saini, 2014)	59.08	–	–	91.69	0.62	–	–	–	0.36	–	2.08		–
Sahmaran and Yaman (Sahmaran and Yaman, 2007)	49.55	13.34	8.51	71.4	3.08	11.31	1.70	–	4.10	1.99	2.74	325.8	2.01
Sounthararajan and Sivakumar (Sounthararajan and Sivakumar, 2013)	58.9	33.4	5.86	98.16	1.28	1.02	0.12		0.38	–	2.2	–	2.48
Saravanakumar and Dhinakaran (Saravanakumar and Dhinakaran, 2013)	56.6	33.71	3.97	94.28	0.16	1.07	0.18	2.1	0.42	1.02	–	–	–
Sahmaran et al. (Şahmaran et al., 2009)	54.13	25.73	6.43	86.29	0.47	2.21	0.11	–	2.12	4.33	1.34	–	2.08
	48.08	25.87	4.54	78.49	0.73	10.07	0.55	–	1.46	1.22	1.01	289	2.27
Mardani-Aghabaglou and Ramyar (Mardani-Aghabaglou and Ramyar, 2013)	49.70	17.01	8.87	75.58	1.66	10.88	2.52	–	5.95	1.30	–	306	–

28 days of curing, while samples with finer grains had the highest density. The samples with unsieved FA had a higher density than samples with FA of 45–75 μm.

Workability

Nath et al. (Nath and Sarker, 2011) demonstrated that as the concentration of FA increased, the slump increased. In comparison to the reference concrete, an increase in slump height of 16.67 and 6.67 % was recorded with 30 % and 40 % FA substitution, respectively, at a 0.29 w/b ratio. As the FA proportion increased from 20 to 30 %, the slump height of the concrete decreased by around 8 % to 20 %. Siddique (Siddique, 2004) reported that slump heights in HVFAC increased by 20, 25, and 35 mm, respectively, as compared with the control sample, at replacement levels of 45, 50, and 55 % FA.

According to Antoni et al. (Antoni and Hardjito, 2015) a flow table test conducted with ASTM standards indicated that using up to 30 % FA as a replacement for cement increased the workability of fresh mortar. The presence of FA also reduced the superplasticizer (SP) demand. According to a comparative study (Nguyen et al., 2018) of mortar and concrete with wet and dry FA of up to 30 %, the wet FA was more workable than a cement-only mix. At the 30 and 50 % FA replacement levels, the slump height increased by 33.33 and 83.33 % at 0.5 w/b and 28 and 85.7 % at 0.4 w/b, respectively, attributed to the reduced viscosity associated with higher FA concentration, which resulted in enhanced flowability and slump (Ikotun et al., 2017).

However, according to the findings o Fantu et al. (Fantu et al., 2021) replacing cement with FA by up to 10 % increased the slump values. In contrast, substituting more than 10 % of the cement with FA reduced the workability of fresh concrete. Conversely, due to the dispersion of cement particles by SP, slump values of concrete with SP increased while partial substitution of cement with FA was up to 20 %.

The workability of concrete with recycled coarse aggregate (RCA) increased as the percentage FA replacement level increased. Slump height increased by 0, 14.2, and 21.42 % when FA was replaced with OPC by 20, 35, and 50 %, respectively, compared to recycled aggregate concrete (RAC) without FA (Tangchirapat et al., 2013). Kurda et al. (Kurda et al., 2017) observed that when 30 % or 60 % FA was used in

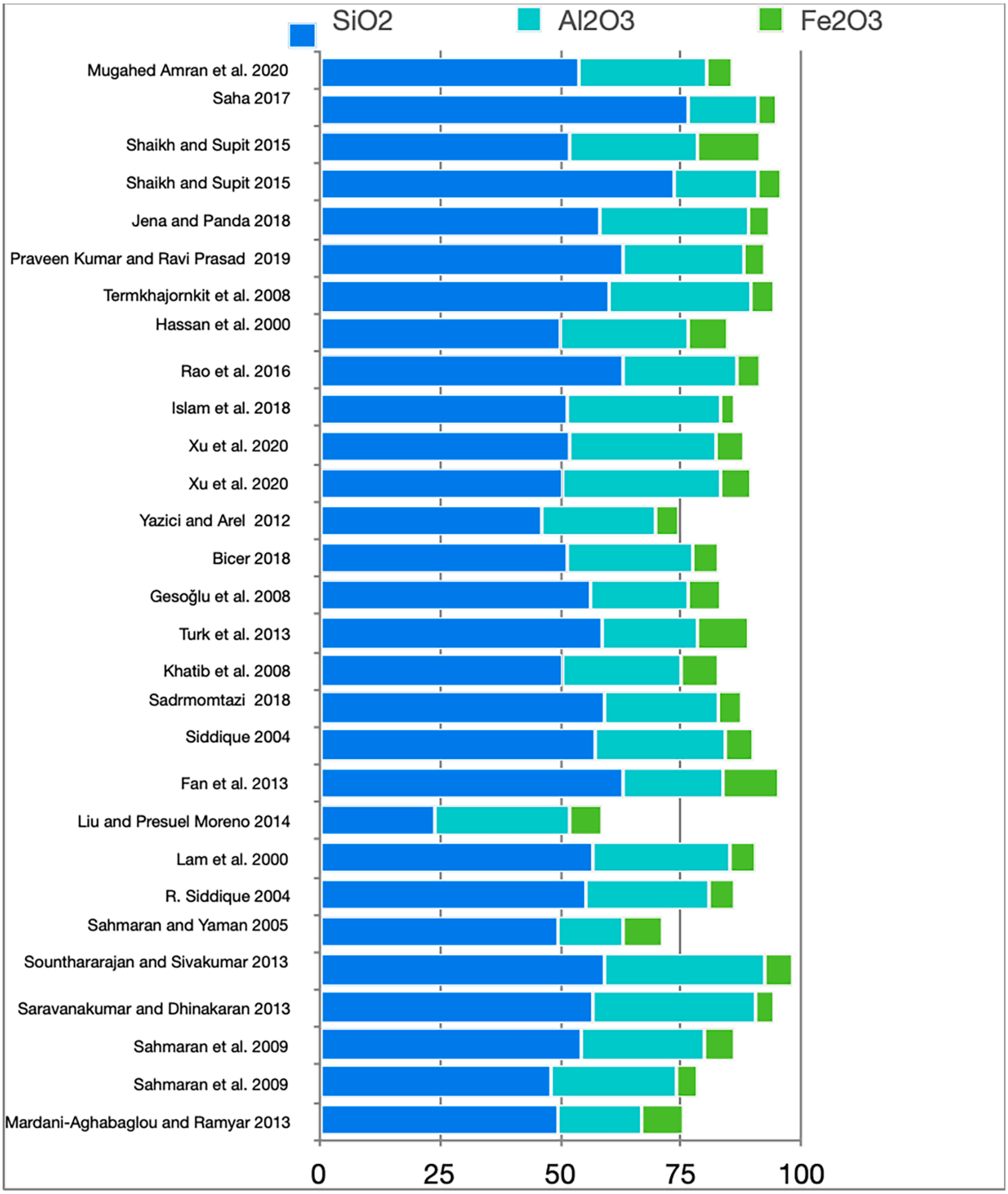

Fig. 2. Proportion (%) of SiO_2, Al_2O_3, and Fe_2O_3 in FA used in the studies.

place of cement in RAC, the amount of water required to achieve the desired slump value of the mix with or without SP decreased. Another investigation (Revathi and Nikesh, 2018) found that adding 10, 20, and 30 % FA as cement replacement increased slump height by 30, 60, and 80 mm, respectively, compared with control RAC.

In their study Yurdakul et al. (Yurdakul et al., 2014) found that increasing the replacement dosage of class F FA for a given w/b ratio resulted in improved workability of binary mixtures, attributed to the fact that class F FA reduced friction between particles. At 8 % nominal air content, binary mixtures containing 15 % and 30 % class F FA produced the highest slump of 280 mm. Furthermore, class F FA admixed concrete had better workability (Fig. 4). Additionally, the study found that increasing air content at a constant w/b ratio resulted in a modest increase in workability. According to a study on the influence of FA and plastic waste on concrete (Paliwal and Marua, 2017), when 20 % FA was combined with 0.6 % shredded polythene, the compaction factor increased from 0.91 to 0.931 compared to the reference sample.

According to the above studies, increasing FA dosage in OPC improves workability for various reasons, including that FA contains smooth spherical fine particles that act as SP and miniature ball bearings that release trapped water within cement particles and provide lubrication (Kurda et al., 2017; Gencel et al., 2011). FA shortens friction between aggregate and concrete and reduces the viscosity of the mix, which also contributes to improved workability (Ikotun et al., 2017). According to Paliwal et al. (Paliwal and Marua, 2017) the FA particles are spherical, and they coat and lubricate the aggregate particles, reducing friction between the aggregates and between the concrete and the supply pump. This may increase the workability and pumpability of

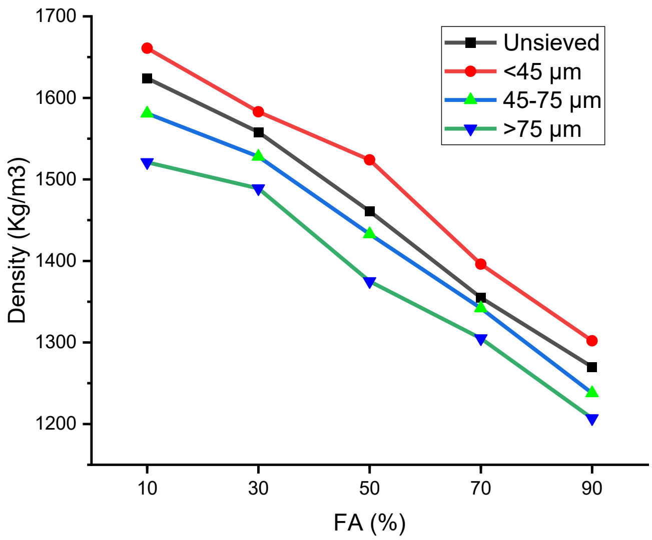

Fig. 3. Variation of the density according to FA replacement and the grain diameter (Bicer, 2018).

concrete. Furthermore, FA particles adsorb on the surfaces of oppositely charged cement particles, preventing them from flocculating. As a result, a large amount of the water is released, thus lowering the water demand for particular workability.

Effect of FA on properties of hardened concrete

Compressive strength

In a study of Saudi-FA-based concrete with a high proportion of class C FA by Mugahed Amran et al. (Mugahed Amran et al., 2020), the CS decreased with a rise in FA percentage from 10 % to 50 % at all ages up to 365 days. A similar observation was reported by Liu and Presuel-Moreno (Liu and Presuel-Moreno, 2014). According to Mugahed Amran et al., in both reference concrete and FA concrete, the CS increased with age due to the continued hydration of OPC and the increased pozzolanic reactivity of FA, respectively. A partial replacement of 50 % OPC with FA reduced the concrete CS by 57.34, 41.61, 37.50, 29.42, 28.32, and 35.52 %, respectively, at 3, 14, 28, 56, and 91 days and 1 year. According to Liu and Presuel-Moreno, when limestone and granite were used as coarse aggregates, the 28-day CS decreased by 38.72 and 49.68 %, respectively, as the FA concentration increased from 20 to 50 %. However, the long term strength, at more than 600 days, the reduction was only 7.12 and 10.62 %, respectively. FA with limestone offered a higher strength compared to FA and granite combination. According to Mardani-Aghabaglou and Ramyar (Mardani-Aghabaglou and Ramyar, 2013), when the cement was partially replaced with FA, the strength decreased as the FA content increased, which was attributed partly to the higher w/b ratio partly to FA contributing less strength than cement. However, when the aggregate was partially replaced with FA, the strength of the concrete increased faster and more than the control concrete, owing to the improved compactibility.

According to Saha (Saha, 2018) the CS of class F FA concrete reduced after 28 days of curing, and the strength decreased sharply with increasing FA concentration. On the other hand, due to pozzolanic reactions, the CS of 30 and 40 % FA concrete increased gradually up to 180 days but remained lower than that of reference concrete until 360 days. Increasing the volume of class F FA resulted in poor CS due to a lack of lime. Concrete containing FA hydrates slowly, leading to low CS in the early ages. The CS of the 10 % FA samples increased rapidly from 7 to 56 days after curing, after which the strength gain became steady. CS of concrete samples containing 20 % FA increased rapidly from 7 to 90 days of curing, while the strength of concrete containing 30 % and 40 % FA increased rapidly from 7 to 180 days of curing, after which a steady increase in strength was observed. After a year of curing, the FA samples had CSs of 88, 82, 87, and 83 % of the control concrete.

The use of 30 % class F FA in concrete with Ferronickel slag (FNS) as a sand replacement caused a reduction in CS. The reduction of CS of FA concrete mix is due to low calcium content (0.6 %) (Saha and Sarker, 2017).

Shaikh et al. (Shaikh and Supit, 2015) examined the durability and CS properties of HVFAC containing ultrafine FA (UFFA). Concrete with 8 % UFFA had the highest CS at all ages. With the inclusion of 8 % UFFA, the early age CS of HVFA cement was improved. The most substantial improvement of almost 200 % in CS was observed in HVFAC, containing 52 % FA and 8 % UFFA, after 3 days. Additionally, the inclusion of 8 % UFFA increased the long-term (90 days) CS of ordinary concrete and HVFAC containing 32 % FA by approximately 55 and 10 %, respectively. The small particles of UFFA and high amorphous content accelerated the pozzolanic reaction, filling the pores in the concrete and enhancing its CS. Small FA particles with a high surface area and amorphous silica content imparted the pozzolanic reaction and increased strength over a longer time than Portland cement (PC) (Saha, 2018).

Jena and Panda (Jena and Panda, 2018) investigated the combined effect of FA and silpozz (a byproduct of rice husk) in marine concrete and noticed that by replacing OPC with 10 % FA plus 20 % silpozz, the CS of concrete increased compared to the control sample. In normal water cured (NWC) ternary samples, the rates of CS increase were 19, 9.5, 7, 6, and 6 %, while in seawater cured (SWC) samples, the rates of increase were 9.5, 20.7, 10.6, 8.3, and 7.8 % after 7, 28, 90, 180, and 365 days, respectively. Among all the samples, including the control specimen, concrete with 30 % FA and 20 % silpozz exhibited relatively

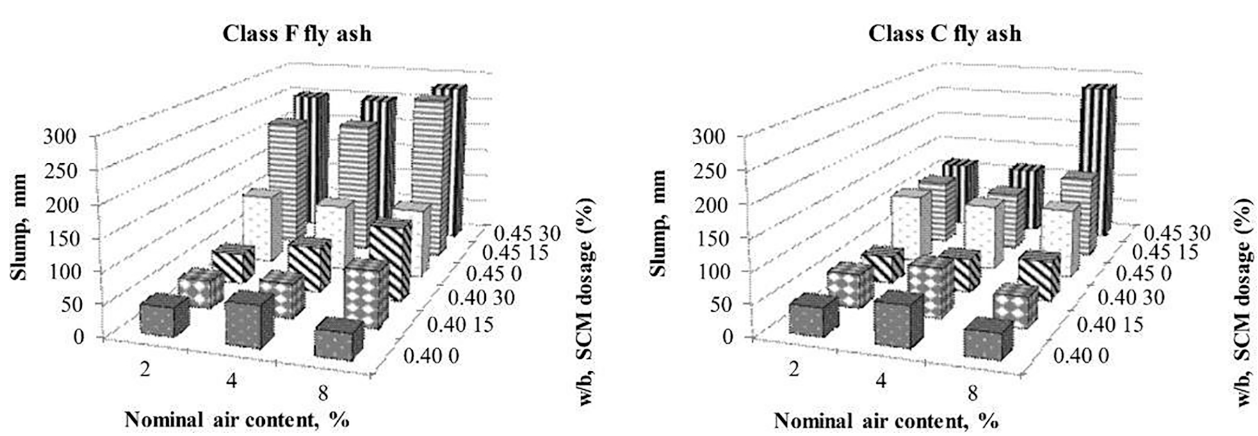

Fig. 4. Effects of w/b, SCM dosage, and nominal air content on the slump (Yurdakul et al., 2014).

low strength at all ages. The study suggested that developing a large CSH gel and dense microstructure in concrete increased its CS.

According to Praveen Kumar and Ravi Prasad (Praveen Kumar and Ravi Prasad, 2019), when OPC was replaced with FA (5, 10, 15, 20, and 25 %), silica fume, SF (4, 6, 8, and 10 %), and lime sludge (LS of 5, 10, 15, and 20 %), the CS of the ternary admixed concrete increased with an increase of FA dosage up to 15 %, then began to decline as the FA dosage increased, but the strength remained higher than the control sample at all w/b ratios of 0.59, 0.39, and 0.32. The CS of ternary admixed concrete of 30, 50, and 70 MPa increased by 42.5, 32.48, and 22.79 %, respectively, when 15 % FA, 10 % LS, and 8 % SF were used in place of OPC. FA is a pozzolanic substance that forms a CSH gel when it reacts with calcium hydroxide (CH) produced by cement hydration (Termkhajornkit et al., 2009). The above study (Praveen Kumar and Ravi Prasad, 2019), reported that the additional CSH gel formation was due to high silica concentration in FA and SF and high calcium content in cement and LS. The formation of the extra CSH gel resulted in increased CS, as Han-Seung et al. (Han-Seung and Wang, 2016) reported. A significant improvement in the CS of the ternary blend of OPC, micro silica (MS), and FA was reported by Audinarayana et al. (Audinarayana et al., 2013).

Fraay et al. (Fraay et al., 1989) reported that the cement paste became gradually denser when the pozzolanic reaction of the FA started. Termkhajornkit et al. (Termkhajornkit et al., 2009) demonstrated that the increase in CS of samples containing FA after 28 days was higher than that of ordinary cement paste, as were the reductions in total capillary pores after 28 days in FA–cement paste.

According to Hassan et al. (Hassan et al., 2000) 30 % FA concrete had 74 % OPC concrete CS after one day and 100 % OPC concrete strength after 28 days. Interestingly, the CS of 30 % FA concrete and 10 % SF concrete was 107 and 109 %, respectively, compared to OPC concrete after one year, indicating a general trend of increasing strength with age, and this is to be related to the noticeable reduction in porosity in FA concrete after 28 days. Fraay et al. suggests that the pozzolanic reaction of the FA in the PC paste can begin only after one or more weeks, when the pore water has sufficient alkalinity for dissolving FA particles. However, Rao et al. (Rao et al., 2016) reported that even at the age of 90 days, fly ash roller compacted concrete (FRCC) with up to 60 % FA had lower strength than the reference mix.

In a study (Islam et al., 2018) on the performance of FA concrete in the freeze–thaw (F-T) process in the marine environment, OPC concrete without FA achieved relatively high CS at early curing ages when compared to FA concrete. Further, the CS decreased with increasing FA %. In seawater and plain water, the strength of all grades of concrete increased during the first 90 cycles of F-T, then began to decline. In a relatively large F-T cycle of up to 365 cycles, the CS of 40 % FA concrete specimens was higher than that of OPC concrete. The CS of FA concrete specimens up to 40 % cement replacement level was higher than that of OPC concrete for relatively large F-T cycles up to 365 cycles. The rise in strength during the first 90 cycles could be owing to the specimens not being completely saturated with seawater. The specimens were significantly saturated by seawater after 90 cycles, and the crystallization of the salts and their combination with cementitious products inside the concrete body resulted in a considerable reduction in CS. The study reported that within 28 days, cement reached its peak strength. Combining the FA with the lime formed during cement hydration produces additional strength. Thus, FA concrete will have lower strength at early curing ages and higher strength at later curing ages than cement concrete. On the other hand, the lime in cement concrete would remain intact, and it would be susceptible to weathering, loss of strength, and deterioration over time.

Xu et al. (Xu et al., 2020) also reported a decrease in 7 days CS as FA level increased in pavement concrete. The control sample had a higher 7 days CS than the FA admixed sample. The 14 days CS of 5 % type I FA (SSA 3800 cm^2/g) concrete, on the other hand, was similar to that of the control concrete but less than that of the concrete containing slag. According to the test results, the concrete with 15 % type I FA had better strength at 28 days than the concrete with 5 % type I FA, while the control specimen had the lowest strength. However, of all the samples examined, the type II FA (SSA 3100 cm^2/g) performed poorly at all phases of CS. The activity of admixtures mostly influenced the rate of hydration. In this study, slag had higher activity than type I FA, while type II FA had the lowest activity and required a longer period to hydrate. The study summarises that the activity of supplementary cementitious materials (SSMs), their dosage, and their age determine the CS. Yazici et al. (Yazici and Arel, 2012) observed that the fitness of the FA has an effect on the CS of concrete at an early age, as the study found that the concretes with the highest degree of fineness had the highest CS at an early age. A similar trend in 28 days of CS according to the particles had been reported by Bicer et al. (Bicer, 2018).

Barbuta et al. (Barbuta et al., 2017) studied the combined effect of FA and glass and polyester fibers on cement concrete properties and observed that the FA dosage and type of fiber influenced the concrete's mechanical properties. The concrete with 10 % FA and 0.25 % glass fibers had the highest CS among the FA admixed concretes, while it was slightly lower than that of the reference concrete. However, the CS of concrete dropped as the FA dosage increased, according to the study.

According to Iqbal et al. (Iqbal et al., 2017) when the FA content in self-compacting concrete (SCC) increased from 100 kg/m^3 to 125 kg/m^3, the CS increased by 13.5 % but decreased by 4.5 % when the FA dosage further increased to 150 kg/m^3 and this strength improvement was more noticeable at 7 and 28 days. The reason for the increase in CS at a particular FA dosage could be that the optimum dosage of FA was required to fill the pores within the concrete. Mehmet et al. (Gesoğlu et al., 2009) demonstrated that the CS of SCC decreased as the FA content increased. By substituting 60 % FA for cement, the CS was reduced by approximately 40 %. However, the combined use of mineral admixtures appeared to mitigate this negative effect of FA as the ternary concrete with 10 % FA and 10 % ground granulated blast furnace slag (GGBS) attained the maximum CS of all samples. Another experiment (Turk et al., 2013) on SCC demonstrated a similar early strength drop as FA dosage increased; however, after 130 days of curing, adding FA up to 40 % enhanced SCC strength but remained lower than the control sample without FA. According to Khatib (Khatib, 2008) a high percentage of FA can be utilized to generate SCC with sufficient strength since the study found that using up to 60 % FA as a cement substitute resulted in the strength of up to 40 N/mm^2.

Sadrmomtazi et al. (Sadrmomtazi et al., 2018) investigated the effect of FA in concrete with SF and found a decrease in 28 days CS as FA content increased; however, the CS of concrete with 10 % FA was the same as that of reference concrete at 7 days and increased up to 14 % in the long term. Additionally, it was observed that introducing 5 % SF into FA increased CS even at early ages and that combining 20 % FA with 5 % SF resulted in a 20 % increase in 90 days strength over the control sample. This is because the addition of finer SF particles enhanced the pozzolanic reaction with calcium hydroxide (CH).

A study of HVFA concrete (Rao et al., 2016) found a 30 % increase in CS for 20 MPa concrete with 35 % FA after 14 days compared to the reference sample, although it was nearly the same after 7 days. At 91 days, however, the increase was only 4 %. At 14, 28, and 91 days, the strength of 40 MPa concrete with 35 % FA increased by 0, 29, and 28 %, respectively. 60 MPa concrete with 35 % FA, on the other hand, showed increases of −9, −3, and 5 % at 14, 28, and 91 days, respectively. Compared to reference concrete, the 60 MPa sample of 50 % FA concrete demonstrated a 9 % improvement in CS at 28 days and 1 % at 91 days. Results showed that a larger HVFA replacement ratio resulted in a slight loss of CS. Previously, Siddique (Siddique, 2004) also observed that replacing 35, 45, and 55 % of cement with class F FA lowered the CS of HVFA concrete by 32, 43, and 48 % at 28 days, respectively, and with curing age, the strength increased. Siddique (Siddique, 2004) also concluded that concrete with 40, 45, or 50 % FA content was strong enough to be used in reinforced cement concrete construction, even at

28 days. Southararajan and Sivakumar (Southararajan and Sivakumar, 2013) suggested that FA concrete would have the same 28-day CS as conventional concrete after 56 days of curing. A CS of 37 MPa was achieved by replacing cement with 40 % FA, which is acceptable as far as waste material utilization is concerned, according to Saravanakumar and Dhinakaran (Saravanakumar and Dhinakaran, 2013). The use of law and high calcium FAs at up to 70 % volume resulted in a self-consolidating concrete with an acceptable CS (Şahmaran et al., 2009). According to this study the HVFA self-consolidating concrete showed significant reductions in 28-day CS, however, these reductions were partially offset later on.

McCarthy and Dhir (McCarthy and Dhir, 2005) suggested that concrete with typical design strengths can be produced with high FA levels. It may, however, result in early strength issues that might be critical in certain aspects of the construction process. Therefore the study also suggests that FA can be used with rapid hardening cement or low energy clinker to address early strength deficits. Filho et al. (Filho et al., 2013) reported that in order to achieve the same CS at 91 days as the reference concrete, the w/b ratio needed to be reduced in the concretes containing 50 % of FA. In SCC, incorporating high volume of coarser FA reduced its water requirement (Sahmaran and Yaman, 2007). The degree to which FA reacted at various curing ages depended on the FA content and w/b ratio of the paste, according to Lam et al. (Lam et al., 2000). Additionally, they noted that using a lower w/b ratio while preparing HVFA concrete could also reduce strength losses.

Fan et al. (Fan et al., 2019) investigated the compressive stress–strain relationship of FA concrete under a thermal steady state. In terms of CS, concrete with 25 % FA, as replacement for cement, outperformed regular concrete in high thermal exposure, with the CS of FA concrete increasing by 105 % at 300 °C, owing to higher hydration under hydrothermal conditions. Additionally, the FA concrete exhibited less CS loss at elevated temperatures up to 900 °C as a result of the further reaction between the reactive silica in the FA and calcium hydroxide under hydrothermal conditions. However, Soni and Saini (Soni and Saini, 2014) observed a decrease in CS when the temperature was raised from room temperature to 120 °C.

In a long-term experiment that lasted more than 150 days, Hashmi et al. (Hashmi et al., 2021) demonstrated that concrete with 40 % FA acquired an acceptable CS, while concrete with 25 % FA has approximately the same strength as plain concrete. In addition, they found that the average increase in CS from 28 to 180 days in FA concrete was higher than the plain concrete, with the highest increment observed at 40 % FA replacement level.

Figs. 5–8 illustrate the CS of reference and FA concrete of varying FA levels at 28 and 90 days, as observed in various studies. It may be observed that the strength difference between FA and reference concrete is greater at 28 days and gradually decreases by 90 days. The difference in the strength is more as the FA level increased.

Figs. 9 to 20 compare the development of CS at different FA levels from 10 to 60 % at 28 and 90 days. From the graphs the influence of w/b ratio on the CS of concrete can be inferred. It can be understood that the CS is inversely proportional to the w/b ratio. Reduction in CS of the concrete samples at higher water to binder ratio is more visible at earlier ages.

Tensile strength

Jena et al. (Jena and Panda, 2018) reported that concrete samples with 10 % FA and 20 % silpozz as a substitute for OPC showed the highest rates of increment in split tensile strength (STS) with 24 and 16.85 % respectively at 28 and 90 days compared to the control concrete. As FA levels increased, STS increased less even with high levels of SP at an early age. Praveen Kumar and Ravi Prasad (Praveen Kumar and Ravi Prasad, 2019) reported that incorporating 10 % LS and 8 % SF with 15 % FA had increased the STS by 19.54, 12.46, and 13.35 % in 30, 50, and 70 MPa concrete, respectively. According to the study, the particle size and surface area had a significant effect on the rate of reactivity. The additional CSH gel formed in the presence of LS resulted in higher strength. Sadrmomtazi et al. (Sadrmomtazi et al., 2018) on the other hand, added SF alone with FA and found a rise in STS. At 28 days, the combined use of 10 % FA and 5 % SF produced maximum STS, 6 % higher than the control sample; however, as the FA percentage increased, STS diminished. The fineness of the FA affected the development of STS at all ages, according to Yazici et al. (Yazici and Arel, 2012). The finer the FA, the more STS was seen in the concrete.

Barbuta et al. (Barbuta et al., 2017) found that adding 0.25 % polyester fiber to 10 % FA concrete increased the STS. However, the study showed that the STS dropped as the FA concentration increased.

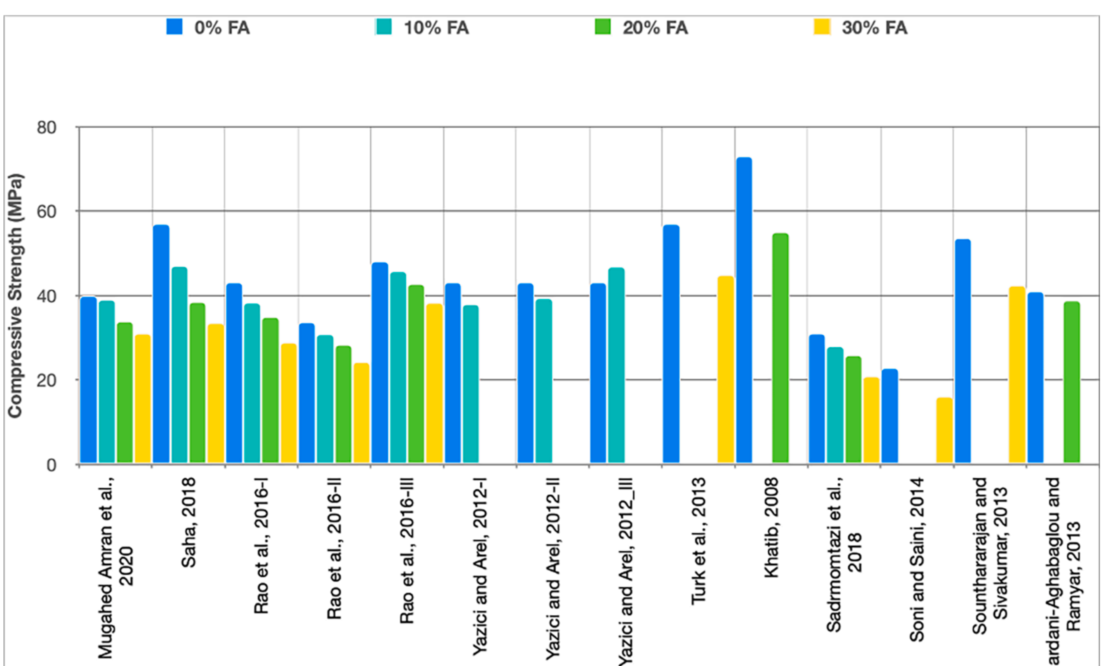

Fig. 5. 28-day CS of reference concrete compared with concrete containing 10, 20, 30% FA.

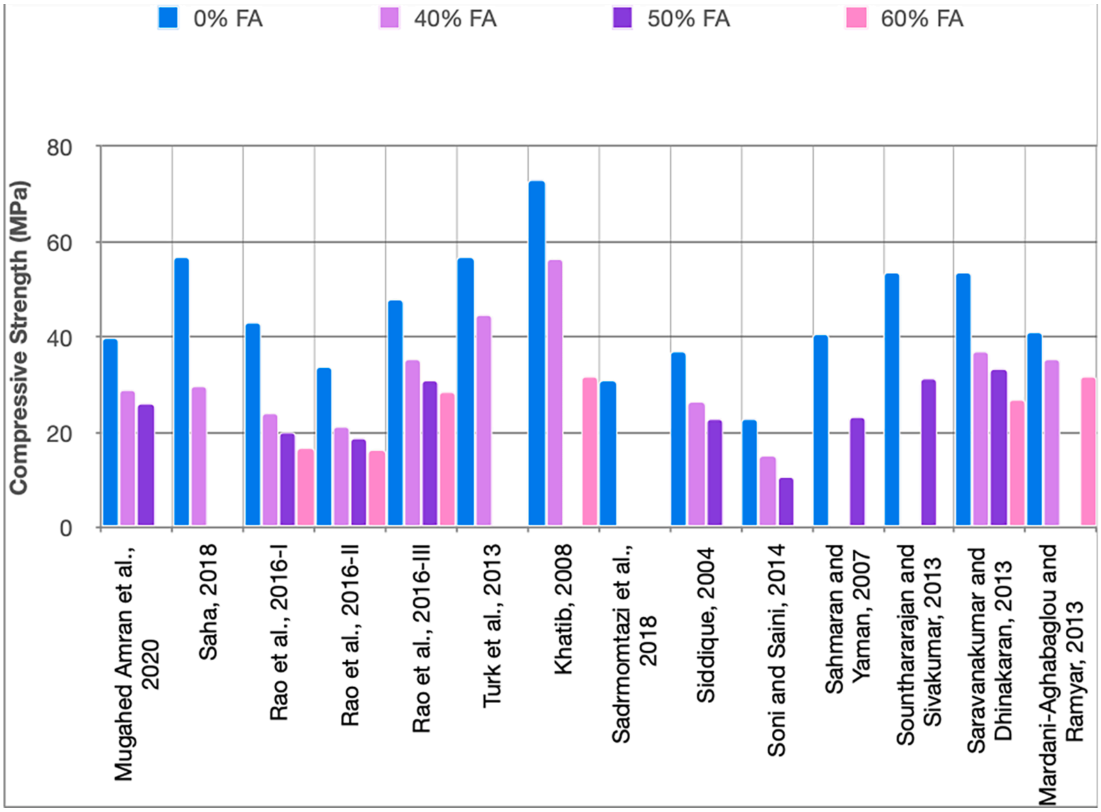

Fig. 6. 28-day CS of reference concrete compared with concrete containing 40, 50 and 60% FA.

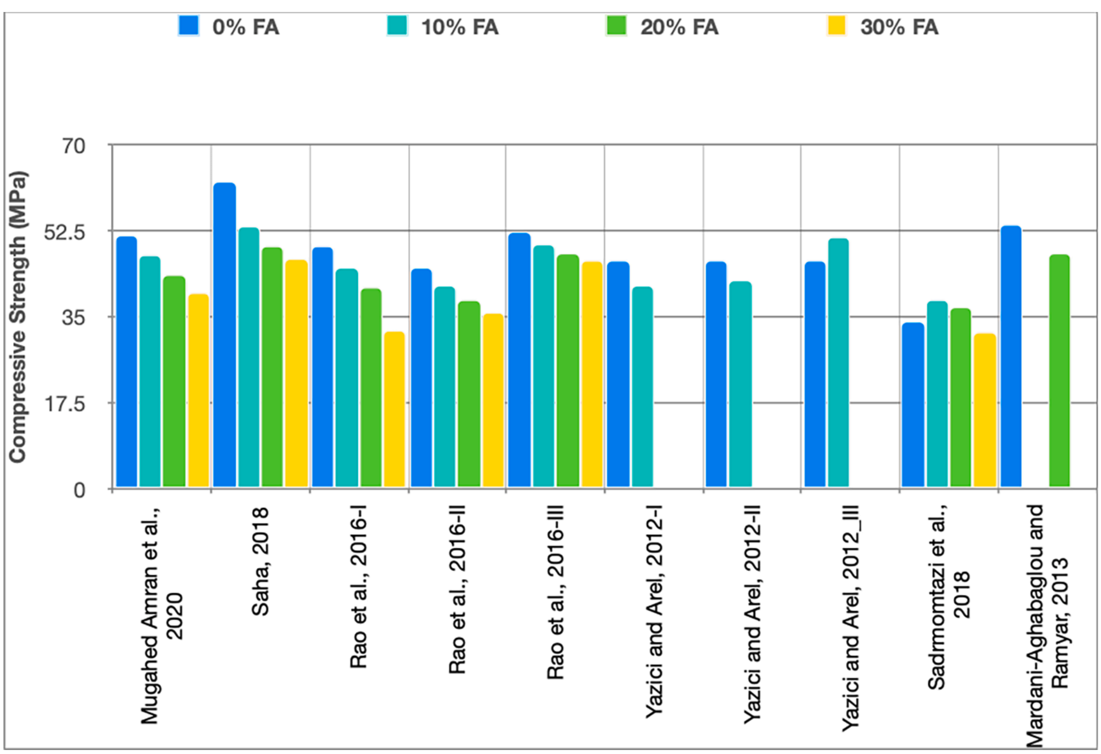

Fig. 7. 90-day CS of reference concrete compared with concrete containing 10, 20 and 30% FA.

As a result, the study suggested employing fibers in FA concrete subjected to tension since they performed well in split and flexure tests.

With the replacement of cement with 35, 45, and 55 % FA, the STS of concrete was reduced by 23, 36, and 49 %, respectively, as observed by R. Siddique (Siddique, 2004) in concrete with a high proportion FA. However, increasing the proportion of san-fibers from 0.25 to 0.75 % increased the STS of FA concrete. According to Saravanakumar and Dhinakaran (Saravanakumar and Dhinakaran, 2013), the 28-day TS was

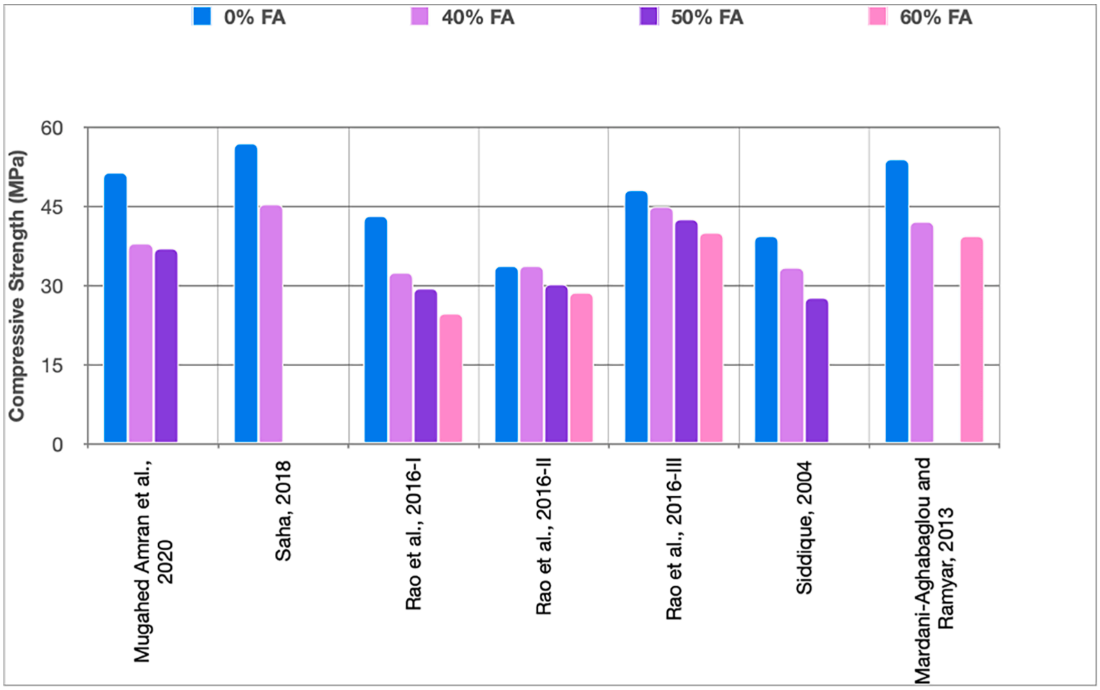

Fig. 8. 90-day CS of reference concrete compared with concrete containing 40, 50 and 60% FA.

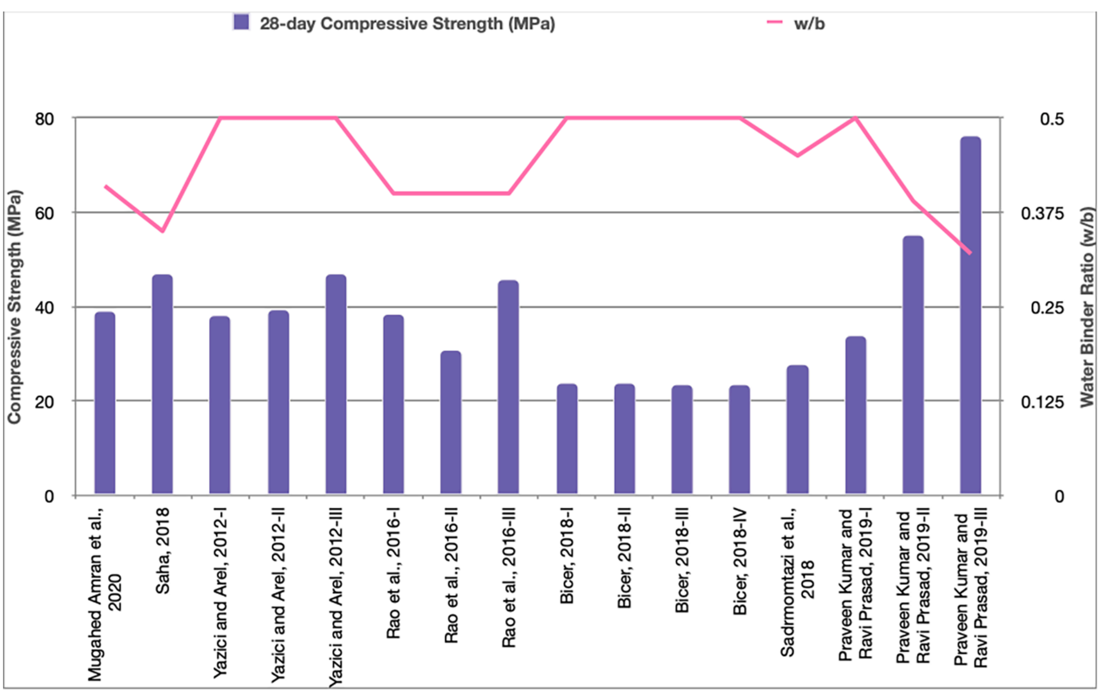

Fig. 9. 28-day CS vs w/b ratio at 10% FA.

reduced by 33.74, 24.13 and 16.16 %, while the 56-day tensile strength (TS) was reduced by only 6.64, 5.47 and 2.93 % compared to the reference concrete at 40, 50 and 60 % FA replacement levels, respectively.

The experimental results (Iqbal et al., 2017) for self-compacting high strength lightweight concrete (SCLWC) showed that increasing FA from 100 kg/m^3 to 125 kg/m^3 and 125 kg/m^3 to 150 kg/m^3 increased the STS by 26 % and decreased by 0.5 %, respectively. According to Soni and Saini (Soni and Saini, 2014) the STS increased as FA replacement levels for cement increased by up to 50 % with increasing age, but declined with increasing volume of FA. According to the study, as a result of the chemical transformation of gel at high temperatures, the matrix boding was weakened and the strength decreased. The graphical depiction in Fig. 21 illustrates the 28-day TS with regard to FA content based on several studies.

According to Hashmi et al. (Hashmi et al., 2021) low calcium FA concrete showed lower flexural tensile strength (FTS) and STS than plain concrete at early ages of up to 28 days, but at later ages, it was comparable to plain concrete. In 180 days, the average STS at 25, 40, and 60 % low-calcium FA replacement levels were 96, 90, and 78 % of that of

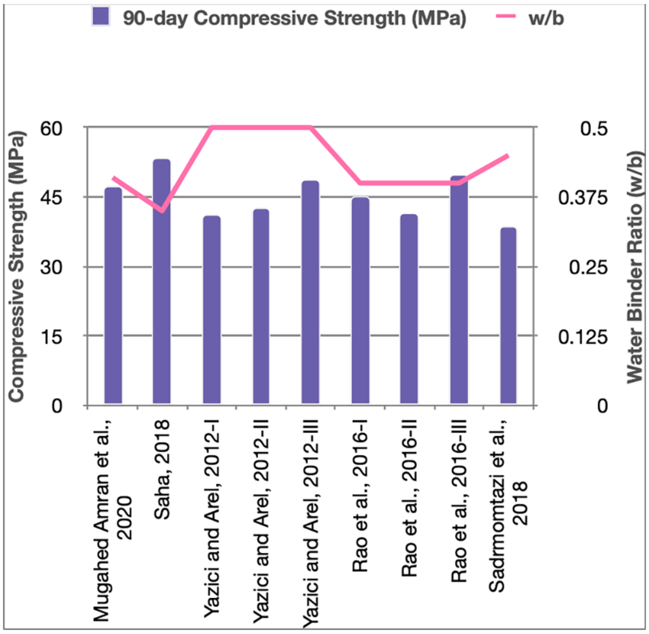

Fig. 10. 90-day CS vs w/b ratio at 10% FA.

reference concrete, respectively, while the average FTS were 90, 74, and 63 % respectively. Concrete mixes containing low-calcium FA develop tensile strength at a faster rate than plain concrete from 28 to 180 days.

Flexural strength

The flexural strength (FS) of silpozz-based marine concrete with 10 % FA was observed to increase compared to the control sample. At 90 days, the rate of increase in FS of the above sample was 44.82 % for normal water curing (NWC) and 49.10 % for saltwater curing (SWC), respectively, compared to the control sample (Jena and Panda, 2018). A ternary blend of concrete containing 15 % FA, 10 % LS, and 8 % SF increased the FS by 20.48, 14.56, and 11.22 % in 30, 50, and 70 MPa concrete, respectively (Praveen Kumar and Ravi Prasad, 2019). According to Barbuta et al. (Barbuta et al., 2017) FS was increased with FA up to 40 % and fiber (glass and polyester) compared to the control sample; the highest FS was found at 20 % FA with 0.25 % polyester fiber. However, a concrete sample with 10 % FA replacement and without fibers exhibited higher FS than the reference sample, and FS decreased as the FA level in concrete increased.

The experimental results in SCLWC (Iqbal et al., 2017) showed that increasing FA from 100 to 125 kg/m^3 and 125 to 150 kg/m^3 increased the FS of SCC by about 10 % and decreased by about 17 %, respectively.

In an investigation by Xu et al. (Xu et al., 2020), at all ages up to 28 days, FS was high in concrete with type I FA (SSA 3800 cm^2/g) up to 25 % replacement compared to the reference concrete sample. up to 25 % replacement compared to the reference concrete. However, compared to the control specimen, the FS of type II FA (SSA 3100 cm^2/g) incorporated concrete was lower at 7 and 14 days but was the same at 28 days. In HVFC, by substituting 35, 45, or 55 % FA for cement, the FS was lowered by 39, 48, and 56 %, respectively. However, increasing the proportion of san-fibers in FA concrete from 0.25 to 0.75 % increased the FS marginally (Siddique, 2004). According to several studies, the 28 day-FS differ according to FA content as seen in the graphical representation, Fig. 22.

Modulus of elasticity

The Modulus of Elasticity (MoE) of concrete is crucial for determining its life duration, and building applications (Bellum et al., 2020) since it indicates the elastic nature of the aggregate and cement paste of concrete in the proper relative ratio (Jena and Panda, 2018).

Durán-Herrera et al. (Durán-Herrera et al., 2011) reported that the elastic modulus of 15 % FA replaced concrete was increased by up to 8 % when compared to the reference concrete. According to Lustosa et al. (Lustosa and Magalhães, 2019) MoE decreased as the FA content increased, as reported by (Rao et al., 2016; Soni and Saini, 2014), and it was noted that the MoE was also affected by the w/b ratio. Jena et al. (Jena and Panda, 2018) noticed that adding 10 % FA as a replacement to

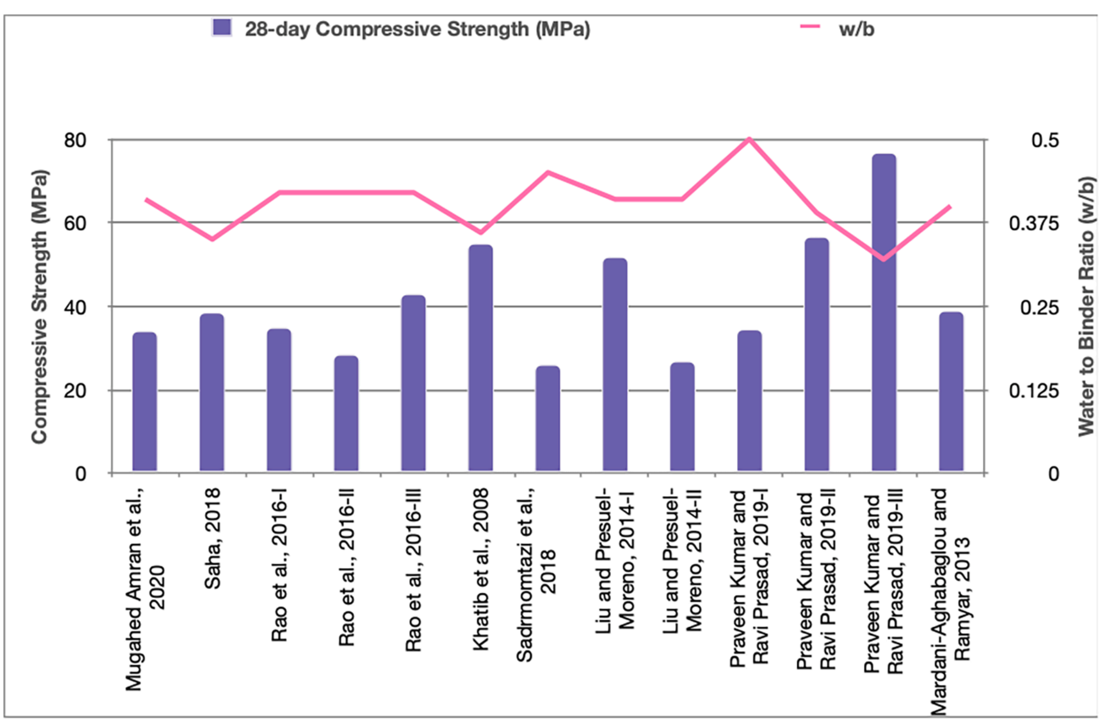

Fig. 11. 28-day CS vs w/b ratio at 20% FA.

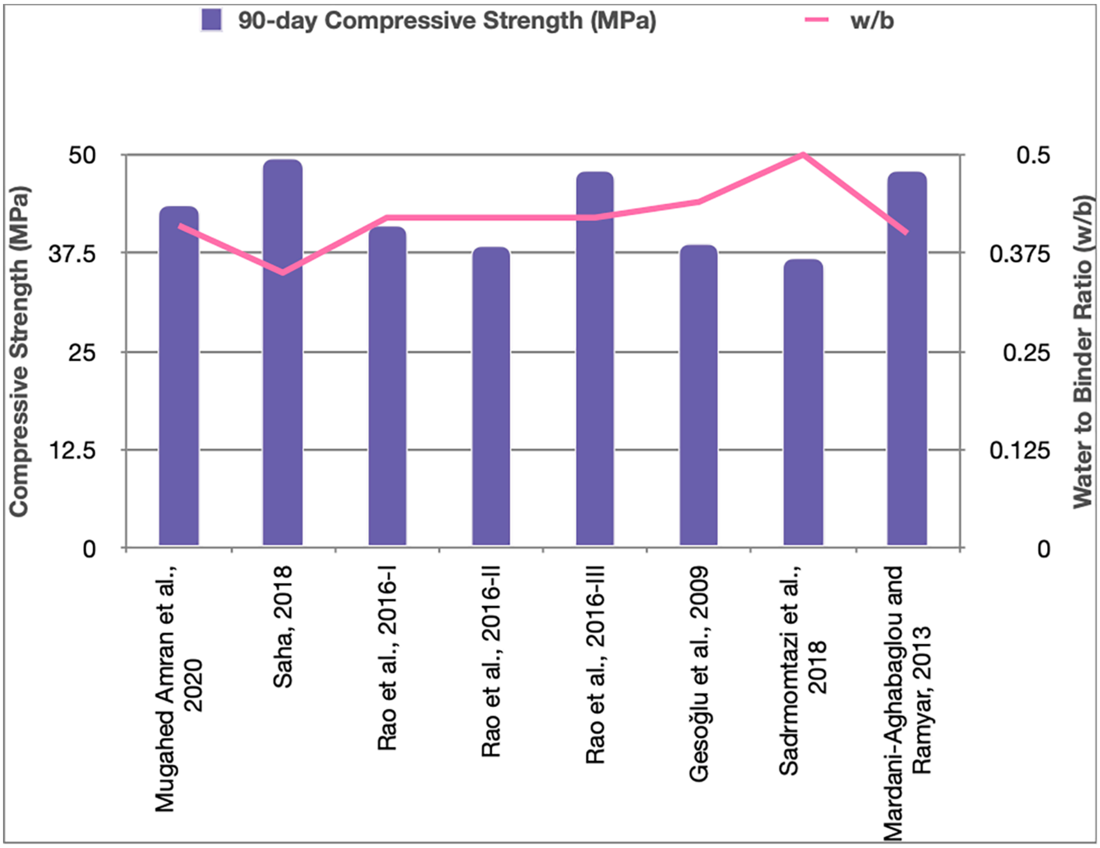

Fig. 12. 90-day CS vs w/b ratio at 20% F.

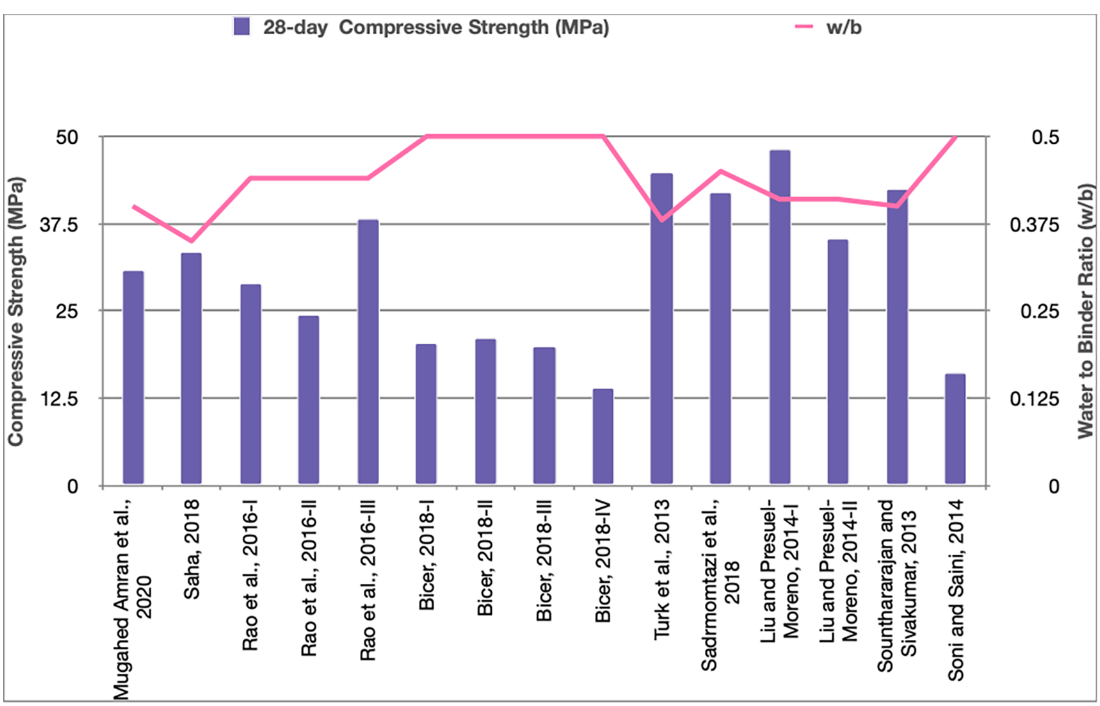

Fig. 13. 28-day CS vs w/b ratio at 30% FA.

silpozz based concrete enhanced the MoE significantly. Sadrmomtazi et al. (Sadrmomtazi et al., 2018) also reported that, at 28 days, the MoE decreased as the FA percentage in OPC increased. However, with the addition of 5 % SF with FA, the MoE improved and was higher than in the control sample. The highest MoE recorded with 10 % FA and 5 % SF was approximately 7.2 % higher than the control sample. According to Kayali et al. (Kayali and Sharfuddin Ahmed, 2013), 50 % FA replaced concrete had a 30 % reduction in MoE compared to control concrete. In

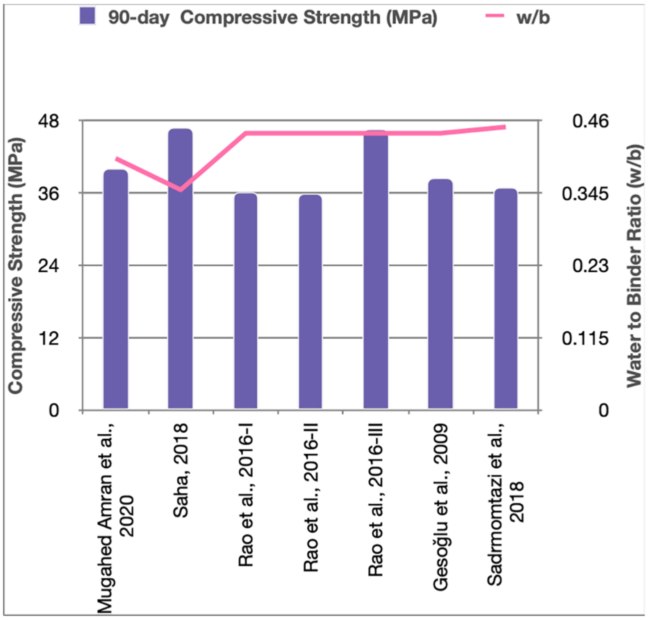

Fig. 14. 90-day CS vs w/b ratio at 30% FA.

SCLWC, MoE increased as FA content increased from 110 to 125 kg/m^3, but only a slight decrease was observed as FA increased above 125 kg/m^3 (Iqbal et al., 2017).

Mardani-Aghabaglou et al. (Mardani-Aghabaglou et al., 2014) calculated the dynamic elastic modulus (DEM) using ultrasonic pulse velocity (UPV) and found that the FA added mortar had a lower elastic modulus than the reference mortar, SF, and metakaolin added mortars. The lower DEM is proportional to the unit weight, and adding FA reduced the unit weight since FA has lower specific gravity than cement. Yoshitake et al. (Yoshitake et al., 2014) found that the tensile Young's modulus was equal to or up to 20 % greater than the compressive Young's modulus in most of the HVFA concrete samples containing 50 % FA with limestone aggregate. Therefore, the study suggested that the general approach of estimating tensile stress based on compressive Young's modulus underestimates tensile stress. Yoshitake et al. (Yoshitake et al., 2012) previously demonstrated that the tensile Young's modulus, rather than the compressive Young's modulus, should be employed for tensile stress evaluation. The graph, Fig. 23, illustrates how MoE varies with FA content according to various researches.

Abrasion resistance

The abrasion value increased as the FA dosage increased, according

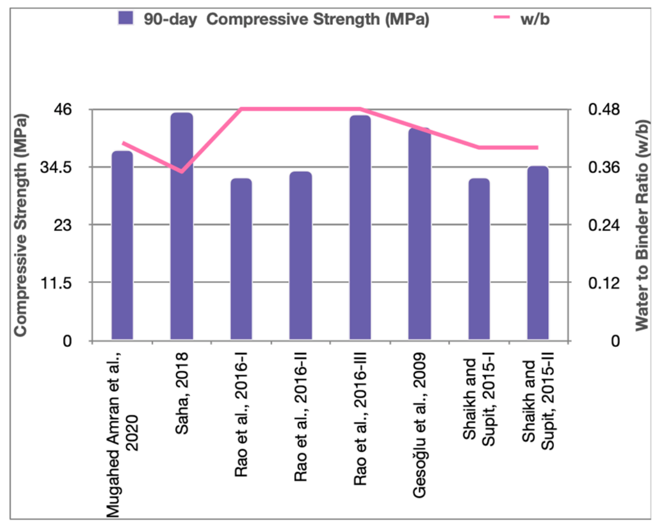

Fig. 16. 90-day CS w/b ratio at 40% FA.

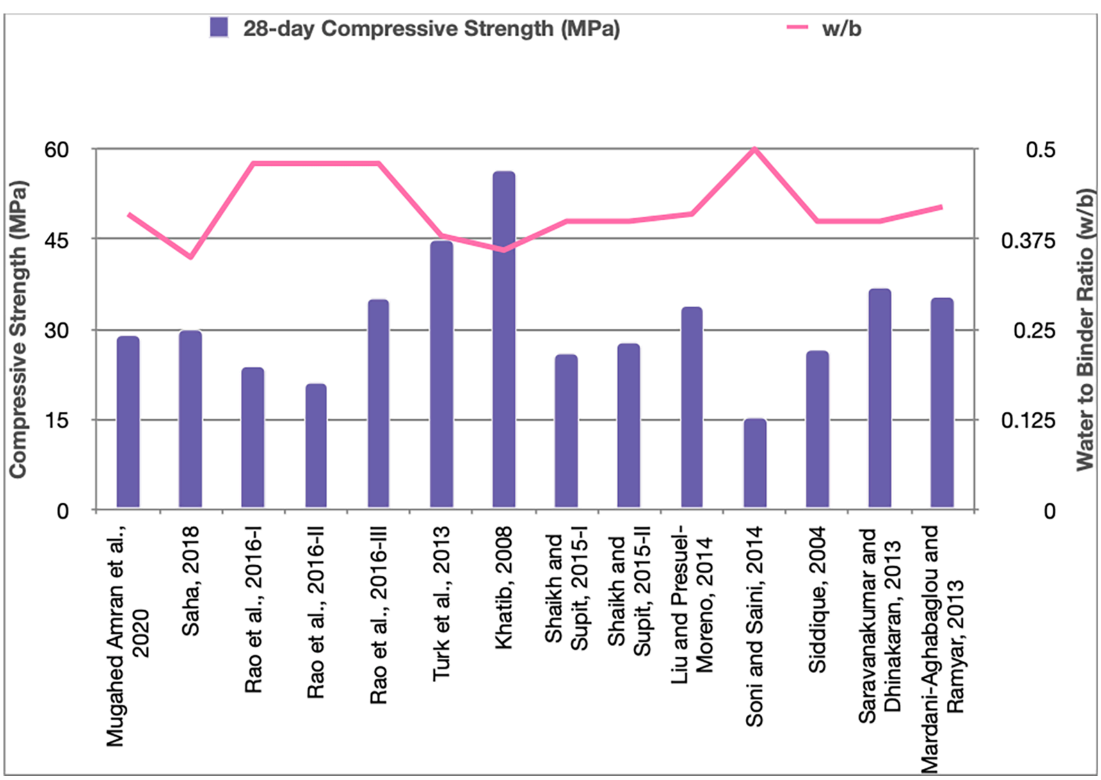

Fig. 15. 28-day CS vs w/b ratio at 40% FA.

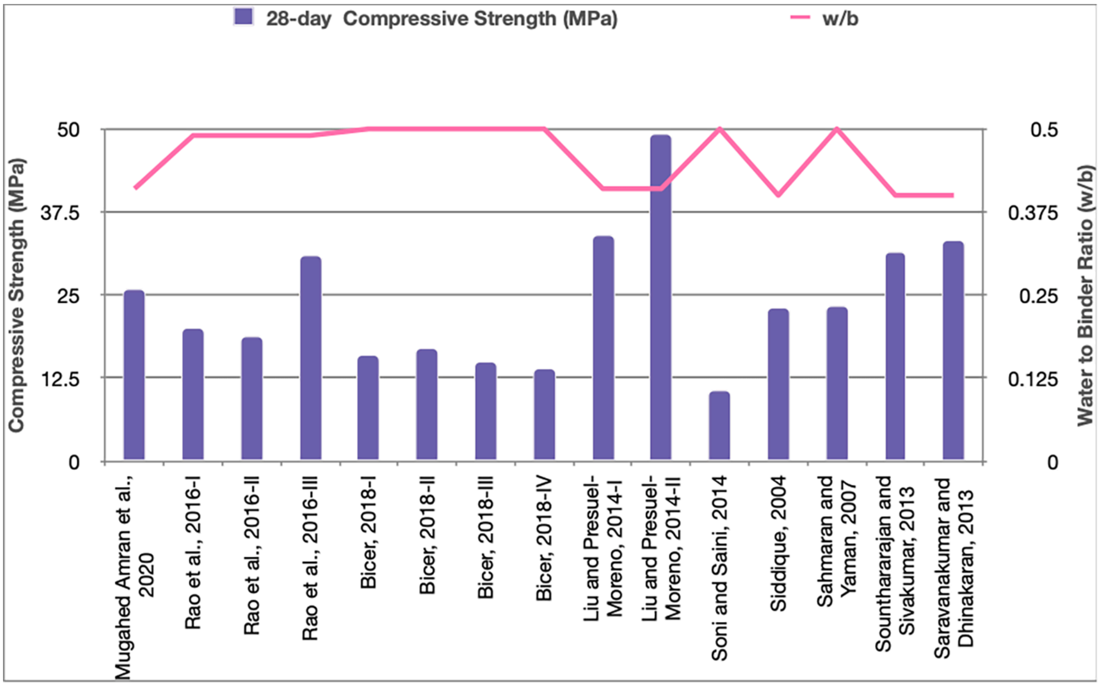

Fig. 17. 28-day CS vs w/b ratio at 50% FA.

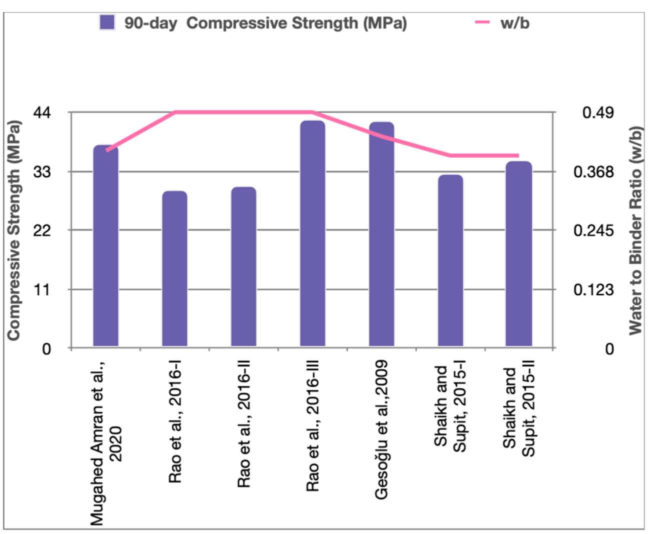

Fig. 18. 90-day CS vs w/b ratio at 50% FA.

to Xu et al. (Xu et al., 2020). At 7 days, the abrasion values of all concrete samples were similar. However, at 14 and 28 days, the abrasion values of the specimens with FA were higher. The investigation results revealed that samples with type I FA of high fineness had higher abrasion resistance (Xu et al., 2020). The test results (Siddique, 2004) showed that the concrete CS significantly influenced the abrasion resistance, as reported by (Naik et al., 1994) in their earlier studies. The study also revealed that the abrasion resistance reduced as the FA dosage increased, and the abrasion resistance increased as the curing age increased as the depth of wear decreased with curing time as shown in Fig. 24. This is in line with a previous study by Naik et al. (Naik et al., 2002). According to Naik et al., the inclusion of class C FA up to 40 % of total cementitious materials did not significantly impact abrasion resistance. However, HVFA concrete had a modest drop in abrasion resistance compared to the reference mixture without FA, notably at FA levels above 50 %. Another HVFA concrete investigation found no higher resistance to abrasion during accelerated tests (Naik et al., 1994).

Interestingly, however, substituting class F FA for sand enhanced the abrasion resistance of HVFA concrete at all ages significantly (Siddique and Khatib, 2010).

From the above literature reviews, it can be concluded that the abrasion resistance decreases with an increase in FA substitution for OPC. Furthermore, as the fineness of FA particles increases, abrasion resistance can also be improved. Reduction is logical as abrasion resistance of concrete is directly affected by concrete CS (Siddique, 2004; Naik et al., 1994; Naik et al., 2002).

Naik et al. (Naik et al., 2002) reported no discernible effect of FA up to 40 % on concrete abrasion. In this study, the abrasion depth decreased with age and increased with abrasion time or FA content. However, mixtures containing 40 % FA demonstrated the same abrasion resistance as FA-free concrete. Beyond 50 % FA content, FA concrete had slightly lower abrasion resistance than control concrete. It was found that as CS increased, abrasion depth decreased.

Impact resistance

The impact resistance of concrete containing 30 % FA was found to be greater than that of ordinary concrete and concrete with 10, 20, and 40 % FA. Compared to plain concrete, the impact resistance of 30 % FA concrete was greater than 10 and 98 % after 60 and 90 days, respectively. At 28 days, however, concrete with 30 % FA exhibited 38 % less impact resistance than plain concrete. After 90 days of curing, replacing 10, 20, 30, and 40 % of FA with cement, the impact value increased by roughly 33, 43, 98, and 26 %, respectively, compared to the control sample (Ramesh et al., 2013). According to Ren et al. (Ren et al., 2019) the impact resistance of RAC decreased gradually as the FA content increased. The value of the impact numbers was relatively higher for 20 % FA, especially at room temperature. Furthermore, as the temperature increased, the impact numbers of the specimen decreased significantly. According to (Kumar et al., 2020), up to 15 % of activated FA replacement in SCC increased impact resistance due to decreased permeability caused by the pozzolanic action. The impact resistance of blended SCC was also decreased when the FA dosage was increased above 15 %.

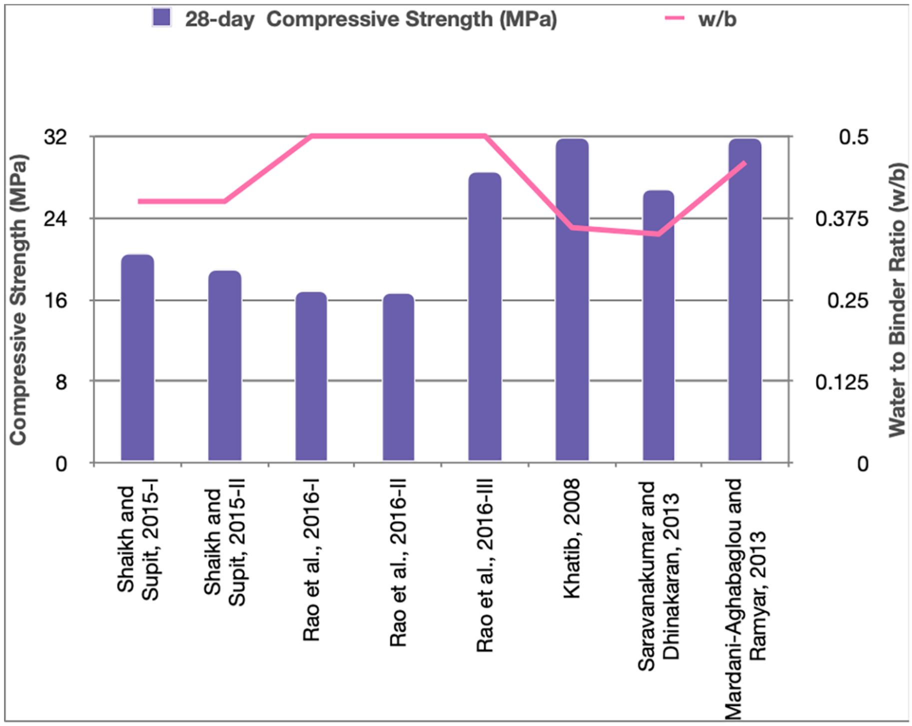

Fig. 19. 28-day CS vs w/b ratio at 60% FA.

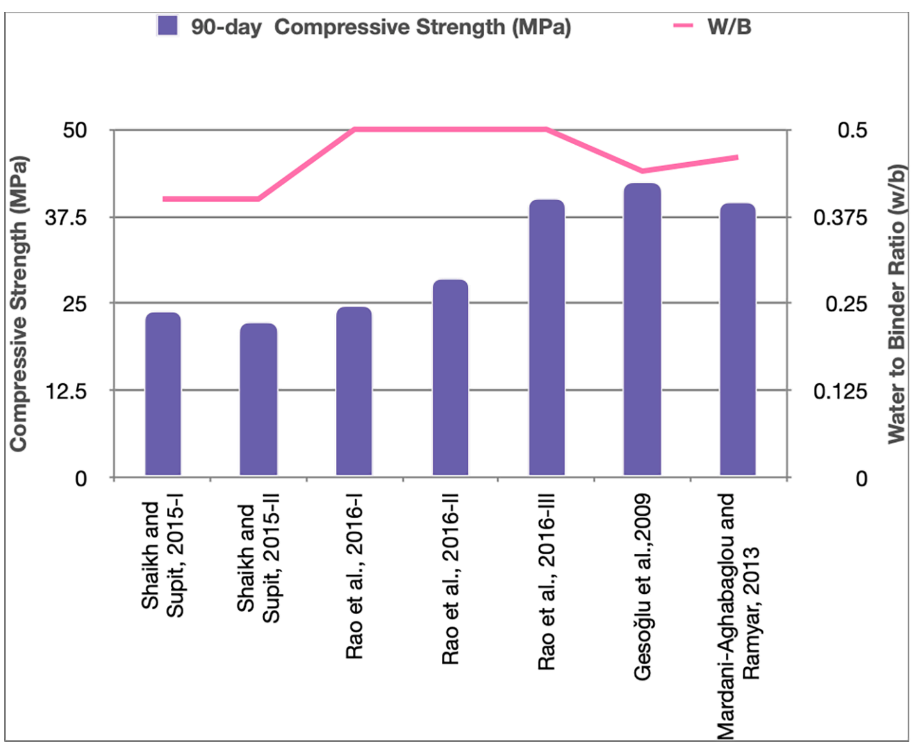

Fig. 20. 90-day CS vs w/b ratio at 60% FA.

Compressive stress–strain behavior/ stress–strain relationship

The stress–strain relationship of FA concrete under a thermal steady-state (Fan et al., 2019) showed that the curvature of the plot, which represents the stress–strain relationship, changed with temperature. Due to the hydration of FA during heating, adding FA to concrete increased the formation of CSH and its more extensive skeleton, lowering the plasticity of the concrete and making it behave more linearly, as shown in Fig. 25.

According to Lam et al. (Lam et al., Feb. 1998), FA concrete exhibited broader and smaller slopes in the descending regions of the stress–strain curve, but PC and SF concrete mixes had sharper bends and faster descending paths. The overall area under the stress–strain curve of FA concrete was about 12 and 16 % bigger than that of PC and SF concretes,

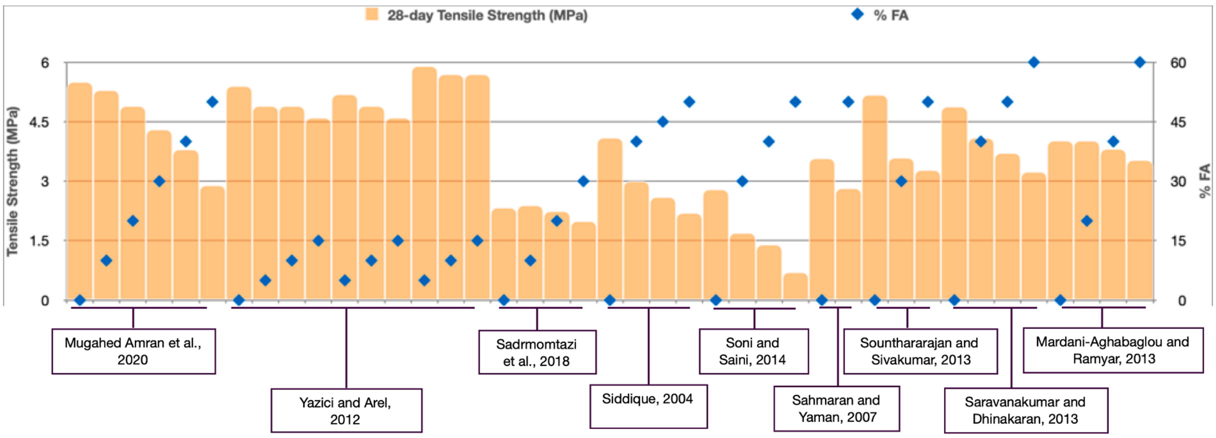

Fig. 21. 28-day TS of FA concrete and respective FA content in percentage in various studies.

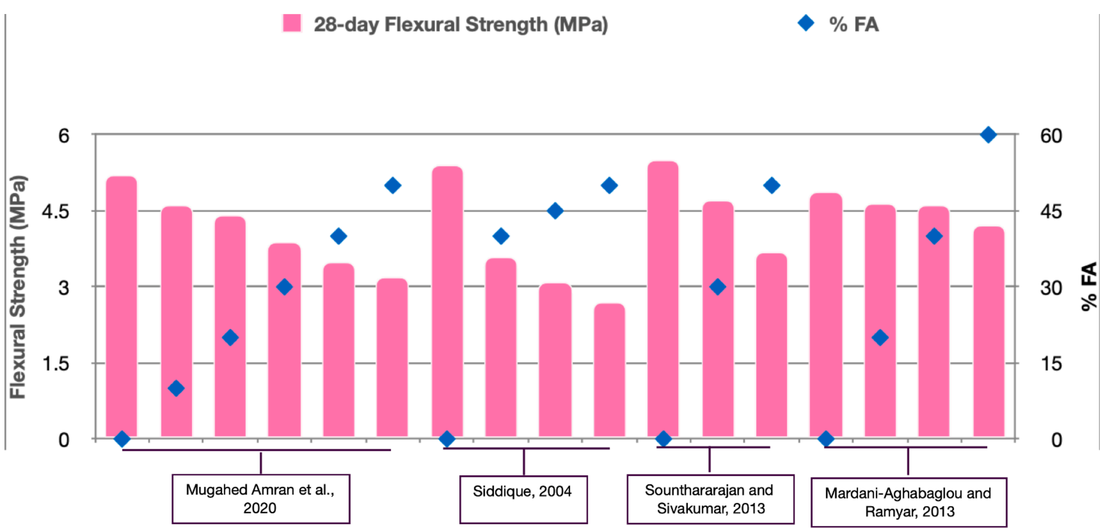

Fig. 22. 28-day FS of FA concrete and respective FA content in percentage in various studies.

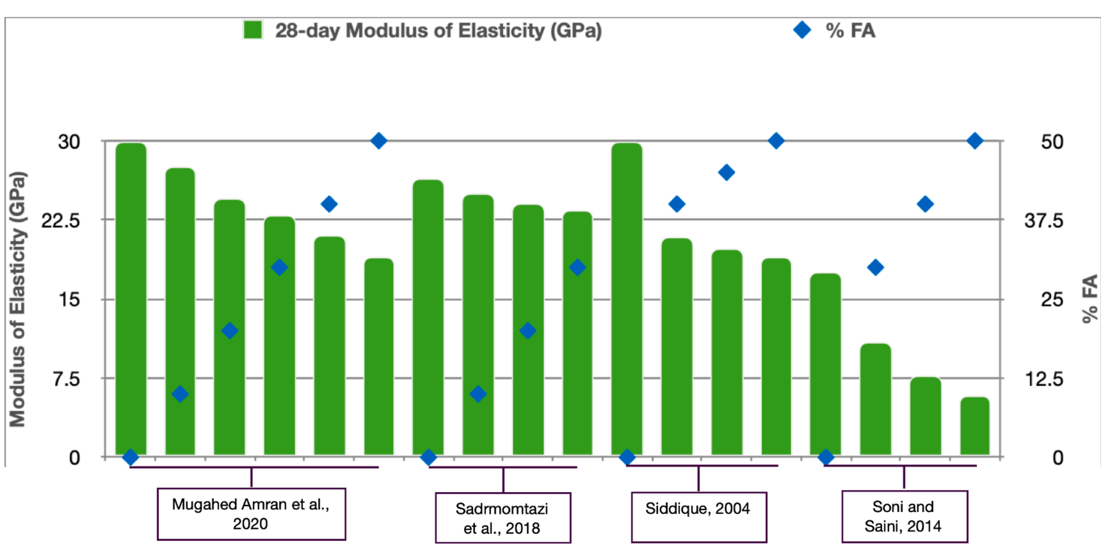

Fig. 23. 28-day Modulus of elasticity of FA concrete and respective FA content in percentage in various studies.

respectively. Concrete's post-peak CS increased when FA was substituted for cement. A further observation was that strain values at peak stress increased considerably with CS. Increasing FA substitution in concrete increased peak stress values (maximum increase of about 40 %) for a given CS.

According to Rao et al. (Ghosh and Kumar, 2019) when FA was

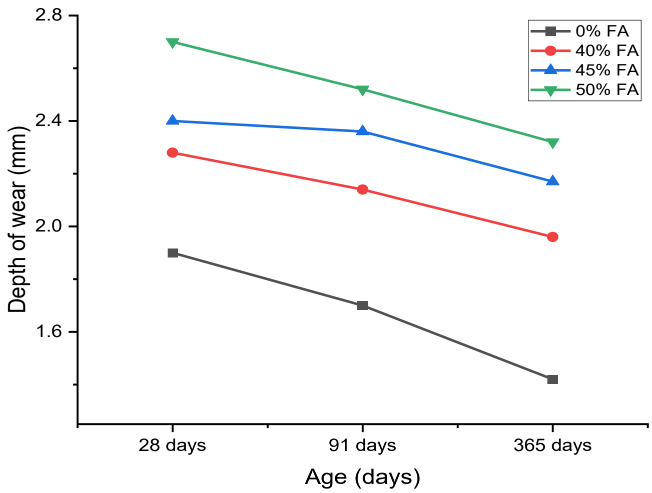

Fig. 24. Depth of wear at 60 min of abrasion (Siddique, 2004).

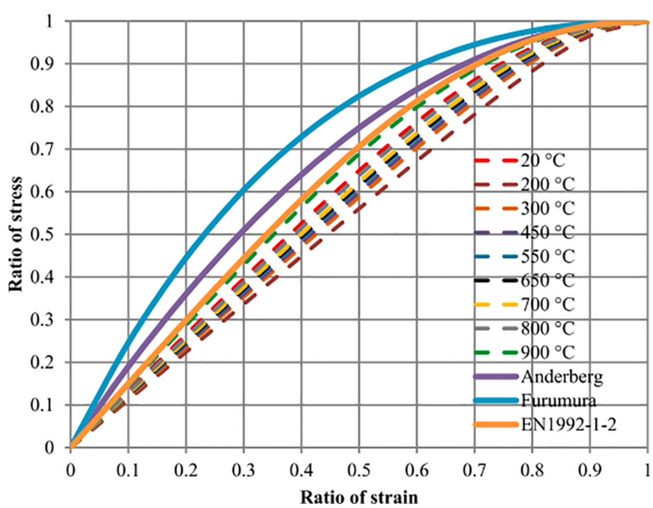

Fig. 25. Variation of normalized stress–strain relations and corresponding curvatures at different temperatures (Fan et al., 2019).

substituted for cement ranging from 30 % to 50 %, the values for concrete containing 30 % FA had a greater peak stress value and lower ductility and stiffness. The strengths of concrete with 40 % and 50 % FA replacements were reduced compared to the reference and 30 % FA concrete. However, when the percentage of FA increased to 40 %, ductility and stiffness improved relative to either reference or 30 % FA concrete.

Non-destructive parameters

Mardani-Aghabaglou et al. (Han-Seung and Wang, 2016) reported a reduction in ultrasonic pulse velocity (UPV) in concrete containing 10 % FA compared to control concrete. The relation between CS and UPV values of the mortar mixtures was plotted to demonstrate the close correlation between UPV values and CS.

According to Hashmi et al. (Fuzail Hashmi et al., 2020) UPV and rebound hammer values reduced as the FA substitution value increased. When evaluated at 28 days and 180 days, the UPV values in reference concrete and concrete with 25 % FA increased from 4.22 to 4.47 km/s. However, as the percentage of FA replacement increased, the UPV value decreased, indicating a decline in concrete CS at higher FA doses. In the rebound hammer test, the reference concrete exhibited slightly higher rebound values than concrete containing 25 % FA at all ages, and the rebound number declined with increasing FA doses. Additionally, CS values reported using UPV were greater than those obtained via experimental and rebound hammer values for all FA replacements. In an another study Hashmi et al. (Hashmi and Baqi, 2022) reported that the UPV value of FA concrete up to 25 % FA was similar to that of plain concrete, while the UPV values of FA concrete at 40 % FA and 60 % FA were slightly higher than that of plain concrete at later ages. According to the author the moisture within the HVFA during early ages was more therefore the strength development was lower at early ages. They also observed that for all percentages of FA and at all ages, rebound hammer results were low compare to the experimental results.

Kurda et al. (Kurda et al., 2018) in their study, demonstrated that the dosage of FA and curing age influenced UPV value. According to the study, the UPV reduced by 5.3, 4.8, and 0 % at 7, 28, and 90 days, respectively, when 30 % FA was added, however, increased by 27 % at 180 days. When 60 % FA was added, the UPV decreased 7·3, 7·6, 4·5, and 1·4% at 7, 28, 90, and 180 days, respectively. According to Rao et al. (Rao et al., 2016) the UPV values decreased as the FA incorporation level increased from 0 to 60 % in FRCC. The UPV data indicated lower values from 3 to 90 days in all FRCC mixtures. Further, with curing age, the UPV value increased. For all incorporation levels and ages of all mixes, the UPV of FRCC mixes was lower than the control mix, as shown in Fig. 26. The decrease of UPV value in FA incorporated high strength concrete at later ages was also reported (Khan, Apr. 2012).

Shrinkage

Early volume change of the concrete is primarily responsible for early age cracking and the subsequent loss of durability of concrete buildings (Mounanga et al., 2004). The current practise of employing low w/c in concrete especially below 0.42, in HPC, may result in excessive self-desiccation, causing concrete's resistance to cracking at an early age to deteriorate (Shen et al., 2022; Zhang et al., 2013; Zhang et al., 2003). These cracks are often associated with autogenous and drying shrinkages of concrete. It is believed that the chemical shrinkage of concrete, which is brought on by the hydration of the cement, is what causes autogenous shrinkage (Mounanga et al., 2004; Yodsudjai and Wang, 2013). Drying shrinkage is, however, due to evaporation of water from the concrete's capillary pores when exposed to the dry environment (Wang et al., 2021). Wang et al. (Wang et al., 2021) considered autogenous shrinkage is a part of drying shrinkage and according to them the drying shrinkage was reduced by combined use of FA and SF compared to SF alone concrete. Gesoğlu et al. (Gesoğlu et al., 2009) suggested that the adverse effect of SF on shrinkage can be lessened by its use in ternary or quaternary mix of FA and GGBS in SCC. The drying shrinkage of concrete is controlled by the factors such as w/b, volume of the paste and the rate of hydration (Saha, 2018). Nath and Sarker (Nath and Sarker, 2011) reported that the FA in concrete reduced drying shrinkage when the w/b and binder content were varied to attain the same 28-d strength of the reference concrete. The crack width and the free shrinkage of the concrete decreased as the content of FA increased, according to Yang et al. (Yang et al., 2007) and furthermore, they stated that increasing the FA to cement ratio from 1.2 to 5.6 resulted in a 50 % reduction in the free drying shrinkage of engineered cementitious composites (ECC). Yurdakul et al. (Yurdakul et al., 2014) also observed less shrinkage as class F FA content increased, though strength was reduced at higher replacement level of FA. Thomas (Thomas, 2007)cited the drying shrinkage of HVFA concrete is generally less than that of normal concrete by virtue of water-reducing properties of FA (Mehta, 2004). Atiş (Atiş, 2003) reported a significantly less drying shrinkage in HVFA concrete with 70 % FA compared to the reference one. It can be attributed to the lowest w/b, the lower amount of hydrated paste and unhydrated cementitious materials which acted as aggregate restraining shrinkage, according to Atiş. Huseien and Shah (Huseien and Shah, 2020) also found in self-compact alkali-activated concrete (SCAAC) that concrete with up to 70 % FA had less shrinkage compared to concrete

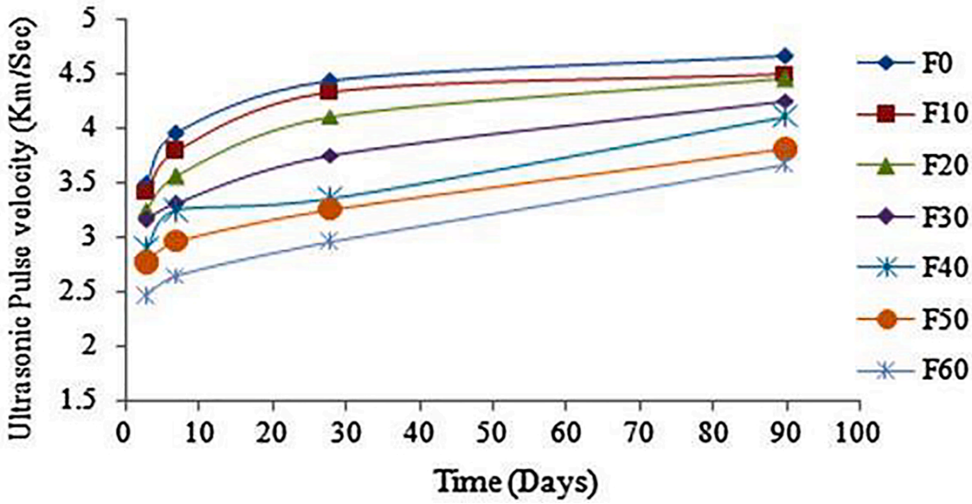

Fig. 26. Progression of UPV with time for FRCC mixes. (Rao et al., 2016).

with 100 % GGBS and improved durability. Based on field experience and laboratory studies, Mehta (Mehta, 2004) noticed greater dimensional stability and resistance to cracking from thermal, autogenous, and drying shrinkages in HVFA concrete with more than 50 % FA. At 80 % FA content, shrinkage at 56 days was reduced by two thirds compared with the control at 80 % FA content and the shrinkage resistance increased as FA content increased in SCC, according to Khatib (Khatib, 2008), identical to the findings of shrinkage in mortars with FA (Kizilkanat et al., 2016). According to Saha (Saha, 2018) the low rate of hydration caused by the low lime content in the class F FA caused the drying shrinkage in FA concrete to steadily decrease. In their study, Mirza et al. (Mirza et al., 2002) noted that drying shrinkage of Portland cement grout with or without FA increased as w/b increased.

Effect of FA on durability parameters

Pore structure/Porosity

According to Rong et al. (Rong et al., 2014), while FA enhanced the hydration process over time, the pore structure gradually became finer and the pore size reduced as curing time increased, resulting in a denser structure in the ultra-high performance cement-based composites (UHPCCs) with FA. It was observed that concrete with FA initially had a high porosity, but this was reduced later age (Wang et al., 2021). In addition, FA, along with SF, optimized concrete pore structure. According to the study, 20 % FA at 0.35 w/b ratio increased porosity in concrete by 12.4 % over the reference mix after 3 days. However, the porosity was observed to be decreased by 20.9 and 16.1 % after 28 and 90 days, respectively. Mercury intrusion porosimetry (MIP) and scanning electron microscopy (SEM) showed that adding FA to concrete reduced overall porosity and pore volume. This is due to enhanced ITZ density and microstructure from the pozzolanic reaction of FA (Sadrmomtazi et al., 2018). According to the investigation performed by Hassan et al. (Hassan et al., 2000), FA addition significantly reduced porosity, which further improved pore structure, strength, and transport properties of high-performance concrete (HPC).

Water absorption, sorptivity, and water permeability

Saha (Saha, 2018) demonstrated that the concrete sorptivity decreased significantly as FA dosage and curing age increased. At 10, 20, 30, and 40 % FA replacement levels, the sorptivity of the admixed concrete was 96, 87, 71, and 68 % of the control concrete. The study observed that FA concrete lost sorptivity for two distinct reasons. The first is that FA has more SSA than cement, and the second is that FA reduces the thickness of the ITZ between aggregates and binders. Jena et al. (Jena and Panda, 2018) reported that water absorption and sorptivity increased with increasing FA content. In this study, seawater cured samples (SWC) showed less absorption and sorptivity than normal water cured (NWC) samples.

As a result of the high fineness of FA, in a F-T environment, water permeability of 40 % FA concrete was 26 % lower than that of plain concrete, which is likely due to its enhanced reaction with the products liberated during the hydration process. Secondary or extra CSH gel produced in the presence of fine FA particles filled all of the pores inside the concrete specimen, making it dense and compact; as a result, the permeability coefficient reduced as the FA content increased up to a certain level (Islam et al., 2018).

It was reported by (Gesoğlu et al., 2009) that the ternary blend of PC, FA, and blast furnace slag (BFS) exhibited a lower sorptivity index than the quaternary blend of PC, FA, BFS, and SF and the control sample. As the FA content increased up to 60 %, the water permeability of the concrete decreased, and this reduction was 50 % at 60 % FA content compared to the control concrete. SCC showed increased water permeability as FA content increased (Turk et al., 2013; Khatib, 2008). However, at 56 and 130 days of curing, water absorption of SCC with FA up to 80 % exhibited less than 2 % water absorption (Khatib, 2008).

Using FA as the cement replacement, the water absorption, permeable voids, sorptivity, and water permeability increased with increased FA dosage compared to reference concrete. While FA as an aggregate replacement, the value of the above parameters declined as FA percent increased but remained lower than the reference sample at all FA dosages. However, all the mixes exhibited less than 3 % water absorption (Mardani-Aghabaglou et al., 2013).

Based on (Bicer, 2018) the water absorption of cement increased as the grain diameter, and FA percentage increased, as shown in Fig. 27. Studies showed that water absorption values are less than their critical value (30 %) at 10 % and 30 % FA ratios. However, the water absorption at 50 to 90 % FA replacement levels was more than 30 %, indicating that FA concrete shouldn't be used where it is exposed to water and against inner wall elements where inner plaster, isolation plaster are used as low-density construction materials.

Chloride ion penetration and chloride permeability

Saha (Saha, 2018) observed a low chloride permeability, i.e., the charge passed less than 2000 C, for class F FA admixed concrete at a curing period of 28 and 180 days based on the rapid chloride

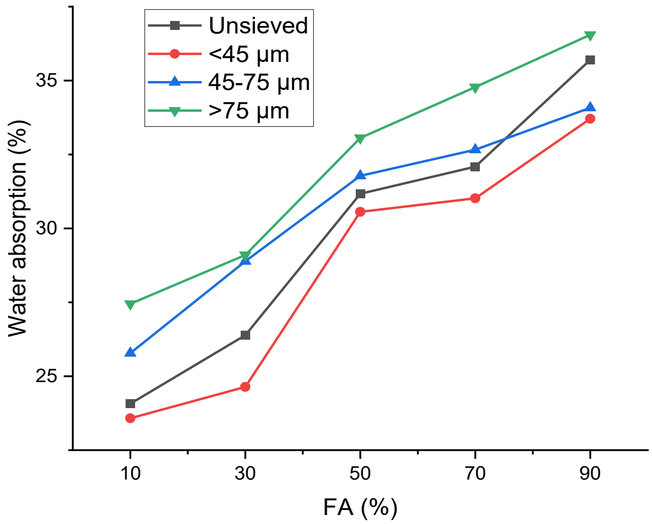

Fig. 27. Variation of water absorption according to FA replacement and the grain diameter (Bicer, 2018).

permeability test (RCPT). However, the permeability was moderate for control concrete, i.e., charge passed was more than 2000 C. The chloride permeability and chloride ion penetration of concrete with 10, 20, 30, and 40 % FA were reduced to 82, 61, 48, and 41 % and 93, 73, 52, and 47 % of control concrete, respectively, at curing period of 28 days. The study suggested that the reduction of chloride ion penetration in FA concrete is due to two key factors: first, FA particles have a high SSA, which lowers interconnecting voids, and second, replacing PC with FA reduces alkali ions (Na^+ and K^+) and associated hydroxyl ions (OH^-) in the pore solution (Shehata et al., 1999). Praveen Kumar and Ravi Prasad (Praveen Kumar and Ravi Prasad, 2019) reported that the pores were filled with the extra paste formed by FA and other admixtures resulting in decreased chloride permeability. Even after 360 cycles of freeze–thaw, concrete with 30 to 40 % FA exhibited a better increase in chloride penetration by 15 and 20 % in plain and seawater, respectively, attributed to the high fineness of FA particles which reduced the size of voids in concrete structure (Islam et al., 2018). Sadrmomtazi et al. (Sadrmomtazi et al., 2018) reported a medium chloride penetration in concrete with FA up to 30 %, and the penetration increased as the concentration of FA increased. However, incorporating 5 % SF with FA brought the concrete to a low chloride penetration level. In contrast, SCC binary concrete with FA up to 60 % showed a low chloride permeability at 90 days (Gesoğlu et al., 2009). However, adding SF or BFS further reduced the chloride permeability to a very low category of ASTM standards (ASTM C, 2012). This is primarily due to the fact that mineral admixture converts large pores to fine pores, a process known as pore refinement (Güneyisi et al., 2007; Chia and Zhang, 2002).

A study in HPC found that 30 % FA reduced chloride migration even at early ages, and the reduction became more pronounced after long-term curing (Hassan et al., 2000). According to Jena et al. (Jena and Panda, 2018) both water-soluble chloride (WSC) and acid-soluble chloride (ASC) decreased by about 15 % in comparison to the control sample when 10 % FA and 10 to 40 % silpozz were used. Both WSC and ASC increased as FA dosage increased but remained lower than the control sample.

Carbonation

An experimental study (Turk et al., 2013) showed that with the increase in FA content in SCC, carbonation resistance decreased. A similar finding was reported in (Khunthongkeaw et al., 2006; Bai et al., 2002). This is because the use of FA reduces the concentration of carbonatable constituents (CH and CSH); as a result, total CaO decreases due to the higher carbonation rates (Papadakis, 2000). The dependence of carbonation resistance on CO_2 diffusion and the amount of carbonatable matter is clear from the well-known square-root-time relation (von Greve-Dierfeld, et al., 2020).

$$x_c(t) = \left(\frac{2D_C.c_s.t}{a_c}\right)^{\frac{1}{2}}$$

Here is the carbonation depth (m), *Dc* is the diffusion coefficient of CO_2 (m^2/s), c_s is the CO_2 concentration at the concrete surface (kg/m^2), a_c is the amount of carbonatable material per unit volume (kg/m^2), t is the time (s).

According to Burden et al. (Burden, 2006) after one year of curing, concrete containing FA at replacement levels of 30, 40, and 50 % exhibited higher carbonation rates than concrete without FA. Kurda et al. (Kurda et al., 2019) reported that using 30 % and 60 %, FA increased the carbonation depth in concrete with a high proportion of FA and RCA by 5 and 6 times, respectively. Additionally, the study revealed that using RCA and FA in combination was more effective at preventing carbonation. Concrete's alkaline reserve decreases due to cement consumption and the pozzolanic reaction of FA. However, as the carbonation time increases, the CSH gel produced by the pozzolanic reaction further fills the pores, increasing the concrete density and thus its resistance to CO_2 intrusion and improving the carbonation resistance (Song et al., 2009; da Silva and de Oliveira Andrade, 2017). Additionally (Kurda et al., 2019; Limbachiya et al., 2012; Sim and Park, 2011; Kou and Poon, 2013) reported that with the combined use of RCA and FA, the carbonation coefficient increased but remained lower than the individual addition of FA and RCA. Because the quantity of $Ca(OH)_2$ in RCA significantly compensates for the amounts of $Ca(OH)_2$ consumed by SiO_2 in FA, indicating using FA with RCA in concrete is beneficial. Bouzoubaâ et al. (Bouzoubaâ et al., 2010) reported that the depth or rate of carbonation varies more with the CS of the concrete, the FA concentration, and, to a lesser extent, the moist-curing period than with the type of FA used.

Sulfate attack

Sulfate attack is the expansive reaction between penetrating sulfate and hardened binder phases (Müllauer et al., 2013) and is one factor that affects concrete durability, as it can cause concrete structures to expand, crack, deteriorate, and deform (Ikotun and Ikotun, 2014). The expansion of the concrete is due to the formation of ettringite and gypsum (Tian and Cohen, 2000; Tosun and Baradan, 2010). Since the pozzolanic reactions reduce the quantity of CH and increase CSH, the pozzolanic cement performs better in sulfate solutions (Merida and Kharchi, 2015). Liu et al. (Liu et al., 2013) reported that the addition of FA significantly increased resistance to sulfate attack, owing to FA's pozzolanic reaction; when 40 % FA was added, the sulfate resistance was better than the sample with 20 % FA. A lower expansion of 10 % FA admixed concrete compared to control concrete exposed to 5 % Na_2SO_4 and 4.2 % $MgSO_4$ solution was reported by (Mardani-Aghabaglou et al., 2014) for different curing periods up to 300 days.

The conversion of CH to gypsum occurs simultaneously with the formation of magnesium hydroxide, which is insoluble and reduces the alkalinity of the system. As CSH no longer has hydroxyl ions in the solution, it becomes unstable and is also attacked by the sulfate solution. Therefore, concrete is more susceptible to the magnesium sulfate attack (Mehta and Monteiro, 2006). Vishwakarma et al. (Vishwakarma et al., 2020), reported that FA concrete performed better in a sulfate-rich environment than the concrete modified with nano-particles, indicating that nano-particle FA concrete is not ideal for sulfate-rich environments. An improved sulfate resistance was observed in mortars blended with 25 % FA because of reduced permeability by the pozzolanic action of FA, and reactive aluminates, according to Nei et al. (Nie et al., 2014). It was also reported by (Baghabra Al-Amoudi, 2002) that the use of FA subsides the amount of C3A produced in concrete to minimize the sulfate attack by lessening the undesirable gypsum and ettringite development (Yu et al., 2015). In addition, because of the binder's lower concentration of C3S and C2S, CH production in the hydrated binder was reduced. Furthermore, due to CH consumption during the pozzolanic process, the CH content of the hydrated binder decreased further. As a result, the CSH refines the ITZ and matrix pores by lowering permeability (Mehta and Monteiro, 2006; Vishwakarma et al., 2020; Nie et al., 2014; Baghabra Al-Amoudi, 2002; Yu et al., 2015; Adam, 2010). It is also reported by Nei et al. (Nie et al., 2015) that sulfate diffusion coefficients are reduced with the use of FA in concrete, thus influencing sulfate resistance, suggesting that chemical reactions of FA must be considered for predicting the service life of concrete under sulfate attack.

Additionally, FA type also affects sulfate attacks. The cement paste with 20 % class F FA exhibited 35 % reduced expansion, while class C FA and class O (neither class F nor class C) FA showed expansion similar to OPC paste when exposed to 200 days in a sodium sulfate solution (Bonakdar and Mobasher, 2010). With the use of class F FA, the microstructure of ITZ improved, and 50 % of the air void was filled up by pozzolanic reaction products (Mobasher et al., 2007).

Sahoo et al. (Sahoo et al., 2017) reported that 25 % FA admixed concrete has greater resistance to sulfate solution than control concrete and concrete with 25 % carbonated FA after 28 days of curing and 30 days of Na_2SO_4 chemical exposure. Furthermore, after 60, 90, and 120 days of sulfate solution exposure, the carbonated FA concrete outperforms FA and control concrete in terms of resistance. Carbonated FA concrete, on the other hand, gains strength rather than losing strength after 90 and 180 days of water curing and 30, 60, 90, and 120 days of chemical exposure. In comparison to the control sample, FA concrete is considerably more resistant to sulfate attack.

Alkali silica reaction

Alkali silica reaction is one of the common major durability concerns in concrete (Zheng et al., 2016). Schematic representation of the Ichikawa's ASR model (Ichikawa, 2009) is given in Fig. 28. The alkali-silica reaction (ASR) occurs when available reactive silica in certain types of aggregates reacts with alkali hydroxides in the pore fluid of the concrete, causing significant damage to the concrete (Newman and Choo, 2003; Mindess, xxxx). By incorporating FA, concrete becomes more ASR resistant because the FA reaction consumes alkali, thereby reducing their availability for expansive reactions with reactive aggregates (Mindess, xxxx) Shehata and Thomas (Shehata and Thomas, 2006), reported that as the replacement level of FA increased, alkali content in the mixture decreased, which led to less expansion due to ASR. According to Detwiler (Detwiler, 2092) class F FA had often been employed to reduce the detrimental expansion caused by ASR and has proven beneficial when given suitable dosages. Class C FA, however, is thought to be less effective and must usually be used in higher doses, if ever used. Latifee (Latifee, 2016) observed that the low and intermediate lime FAs were highly efficient in reducing ASR expansion, while the high lime FA was not. An increase in FA dosage, on the other hand, reduced ASR expansion faster in high-lime FA than in low-lime FA.

According to (Shehata et al., 1999) FA with a high alkali content was less effective at lowering the alkalinity of pore solution. The ability of FA to reduce the availability of alkali and hydroxyl ions in solution, on the other hand, was determined primarily by content of calcium and slightly by the content of silica of the specific FA. The study showed that the alkalinity of pore solution increased as the calcium and alkali content of the FA increased and decreased as its silica content increased. In another investigation, Shehata and Thomas (Shehata and Thomas, 2000) reported that different FAs have different safe replacement levels (SRL), restricting expansion to 0.04 % at 2 years. The FA with low to moderate

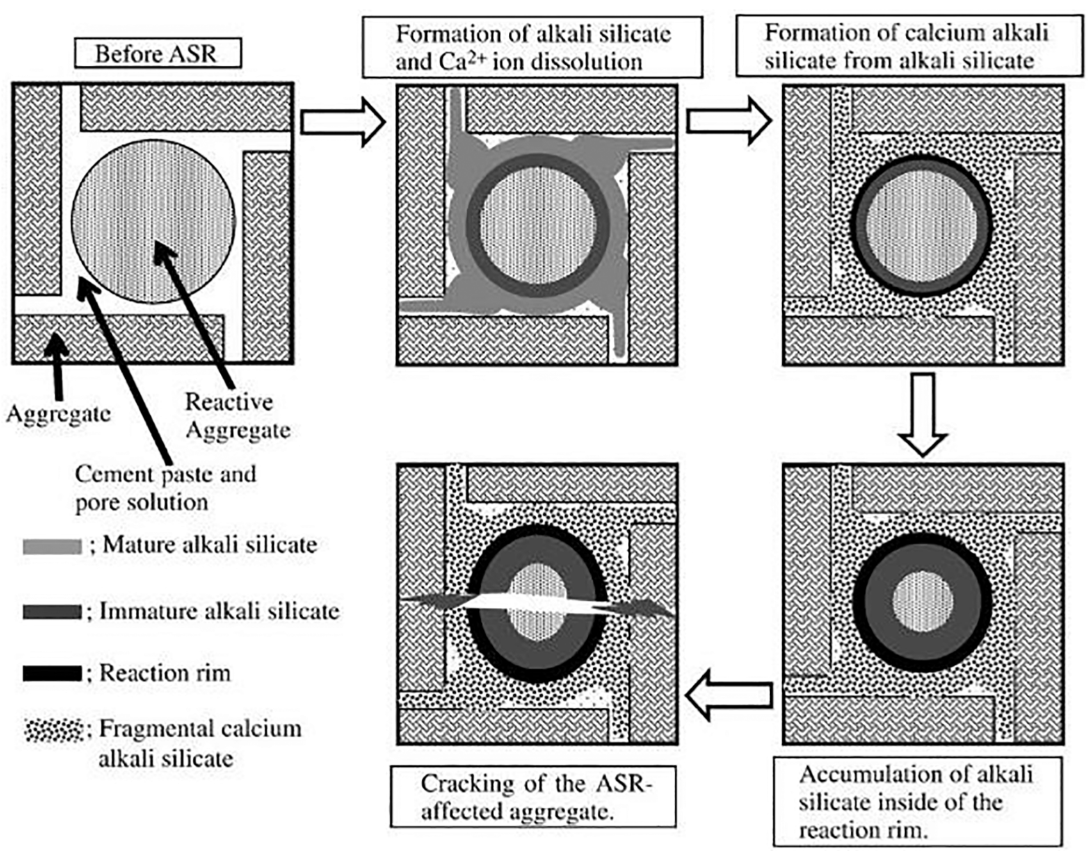

Fig. 28. Schematic representation of mechanism of ASR in concrete (Ichikawa, 2009).

alkali content (i.e., less than 4.0 Na_2O_e), the SRL was between 20 and 25 %. The FA with high-alkali content, the SRL ranged from 40 to 55 %. For the low alkali content FA with the calcium content between 20 and 22 %, the SRL came to be between 25 % and 30 %. For FA with a calcium content of more than 25 % with low alkali contents (1.60 to 2.26 % Na_2O_e), the SRL varied from 35 to 60 %. Therefore, the SRL required to control expansion generally increases as the FA's calcium or alkali content increases or its silica content decreases. Detwiler had suggested that while 25 % was sufficient for most class F FA, it was often not sufficient for class C FA. Latifee also observed that 25 % low lime FA was very effective for highly reactive aggregates. Concrete with 5 % SF and low, moderate and high-calcium FA was found to maintain the expansion below 0.04 % after 3 years (Shehata and Thomas, 2002). It was also reported (Kandasamy and Shehata, 2014) that the combined use of at least 20 % slag and FA reduced expansion due to ASR and maintained expansion of less than 0.04 % after 2 years.

Moser et al. (Moser et al., 2010) found that the binary blends of class C FA exhibited a 25 to 37 % reduction in expansion compared to the control sample; however, ternary blends of metakaolin and class C FA had a slightly higher expansion than binary blends. According to (García-Lodeiro et al., 2007) the mortar expansion due to ASR was reduced from 1.2 % to only 0.1 % using 100 % NaOH-activated FA compared to OPC with siliceous aggregate in 1 M NaOH immersion for 90 days. Thomas et al. (Thomas et al., 2011) observed that class F FA at 25 % and 40 % effectively prevented expansion even when the PC and alkali content of the mix were sufficient to cause significant expansion and damage in mixes without FA. The investigation showed that in 16 to 18 years of field exposure, none of the blocks containing 25 % or 40 % FA exhibited deleterious expansion or cracking. In the study, no alkali was found to be contributed by FA.

Venkatanarayanan et al. (Kizhakkumodom Venkatanarayanan and Rangaraju, 2013) investigated the influence of particle size and chemical composition of FA on ASR. According to the study, mitigation of ASR was more dependent on chemical composition than particle size within the typical range of FA particle sizes of 10 to 30 μm. However, the fineness of FA became significant when its particle size was less than 10 μm. Further, FA fineness played a significant role in preventing ASR in mixtures containing high-lime FA compared to low-lime FA. On the other hand, low-lime FA effectively reduced ASR even without reducing particle size.

According to Vayghan et al. (Gholizadeh Vayghan et al., 2016), who developed a mathematical model the chemical compositions of PC and FA had a significant impact on the performance of concrete against ASR for any given reactive aggregate. According to regression analyses, the study reported that the CaO and MgO from PC and FA and SO_3 from FA promoted ASR, whereas SiO_2, Al_2O_3, and Fe_2O_3 components suppressed it. In a concrete prism test, PC alkalis (Na_2O_{eq}) promoted ASR, but FA alkalis did not affect ASR expansion.

Delayed hydration of free CaO and MgO

Adding FA and slag to cement that contains magnesia reduced its expansion with increasing concentrations, according to Liu et al. (Liu et al., 1998). It was observed that the FA suppressed the expansion more compared to slag at the same concentration. The autoclave expansion values increased with MgO, temperature, and time; however, they were found to be decreased with an increase in FA replacement level (P. wei Gao, , 2007) as shown in Fig. 29. Nawaz et al. (Nawaz et al., 2016) reported that the cement with a higher content of free lime in the FA blended cement showed greater autoclave expansion than blended cement with lower free lime content. Investigation (Nguyen et al., 2019) on the influences of different types of FA on performances of expansive mortars and concretes showed that the use of FA, particularly substandard FA, which contains high CaO, free lime, and SO_3, improved both free and restrained expansion of expansive concrete, compared to standard FA.

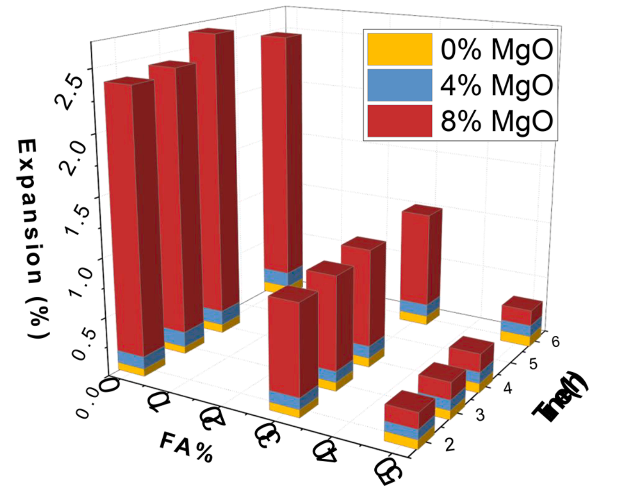

Fig. 29. Effect of FA %, autoclave time and MgO content on autoclave expansion at 2160C temperature (P. wei Gao, , 2007).

Corrosion resistance

According to Shaikh et al. (Shaikh and Supit, 2015) mass loss of rebar due to corrosion in cement concrete was approximately 20 % less than the control sample at a 40 % FA replacement level. The combined use of 8 % UFFA and 32 % FA as an OPC replacement resulted in a mass loss of only 7.16 %. Incorporating HVFA and UFFA improved the corrosion resistance of admixed concrete by reducing porosity and chloride penetration. Jiang et al. (Jiang et al., 2004) reported that large volume low, quality fly ash (LVLQFA) concrete effectively resisted corrosion when tested in 5 % Na_2SO_4 and 5 % HCl solutions compared to the control sample at 56 days and 118 days curing intervals.

According to Choi et al. (Choi et al., 2006) the charge transfer resistance (R_{ct}) of FA concrete was higher than that of OPC concrete. At 0.35 and 0.5 w/b ratios, 20 % FA concrete showed 1.48 and 1.02 times R_{ct} at 140 days immersion and 4.1 and 1.2 times R_{ct} at 250 days immersion in 3.5 wt% NaCl solution respectively than OPC control concrete. The higher corrosion resistance of FA concrete compared to control concrete is attributed to its decreased chloride ion permeability. In other words, the concrete without FA had many surface defects, which allowed water and ions to penetrate, causing corrosion.

Boa at al. (Boa and Topu, 2012) reported that by replacing 15, 30, and 45 % of the FA, corrosion currents decreased, and the time for concrete deterioration to occur increased significantly. However, they were more pronounced in the water-cured samples when compared to the air-cured samples at 28 and 56 days. Due to incomplete pozzolanic reactions in air-cured FA concrete, the concrete became more permeable. Revathi et al. (Revathi and Nikesh, 2018) also found that corrosion currents decreased as the percentage of FA replacement in RAC increased from 10 % to 30 %, attributed to the fineness of FA and its ability to fill the pore spaces in concrete structures. The steel passivity in reinforced concrete was reduced, according to Quraishi et al. (Quraishi et al., 2017) because of a reduction in $Ca(OH)_2$ caused by the pozzolanic reaction of FA, and, at the same time, extra secondary cementitious material was produced, which filled the pores of the concrete, making it thick, and, therefore, providing better corrosion resistance to reinforcement.

Praveen Kumar and Ravi Prasad (Praveen Kumar and Ravi Prasad, 2019) observed a high resistance against corrosion in the ternary admixed concrete of 15 % FA, 10 % LS, and 8 % SF compared to control concrete. The study also found that as concrete grade increased, corrosion resistance increased due to the micro filler effect of the admixtures.

Frost resistance

According to (Zobal et al., 2016) the dynamic modulus of elasticity (DME) decreased with an increase in the freezing-thawing (F/T) cycle and FA replacement level. The study reported that after 50F/T cycles, the DME of 50 % FA concrete decreased almost to zero, while the FS also decreased similarly. After 50F/T cycles, the FS of 50 % FA mixed concrete was only 1.2 MPa, compared to 5 MPa in control concrete.

Concrete containing FA exhibited poor freezing resistance (Xu et al., 2020). The study demonstrated that the F/T mass loss value increased as the FA level increased. Surface F/T mass loss % values of type-I FA (SA = 3800 cm^2/g) admixed concrete were lower and higher for type-II FA (SA = 3100 cm^2/g) admixed concrete for water curing and saturated NaCl solution curing compared to the control concrete after 15 freezing-thawing cycles. Lower mass loss of Type-I FA mixed concrete may be due to the little susceptibility to the migration of portlandite from the dense CSH zones to the air voids.

Increasing FA replacement in alkali-activated blast furnace slag (BFS) concrete increased the FS after 100 freezing cycles; however, a slight decrease in CS was observed, according to Procházka and Boháčová (Procházka and Boháčová, 2020). Mardani-Aghabaglou (Mardani-Aghabaglou et al., 2013) reported that the DEM increased with an increase in FA percent and decreased with an increase in the F/T cycle when FA was used as an aggregate replacement, and it remained higher than the reference sample for all FA mixed concrete. On the other hand, when FA replaced the cement, the DEM decreased as the FA percent increased and decreased as the F/T cycle increased, and it remained lower than the reference sample for all FA mixed concrete, as shown in Fig. 30. Ramesh et al. (Ramesh et al., 2013) found that the 10 % FA mixed mortar reduced CS by 30.7 % after 300F/T cycles compared with the control sample. After 300F/T cycles, however, the 10 % FA mixed mortar outperformed the reference cement mortar in terms of weight loss.

Effect of acid exposure

According to Torii and Kawamura (Torii and Kawamura, 1994) substituting FA for cement significantly improved the mortar's resistance to sulfate attack, owing to the mortar's high impermeability and low CH content. However, the efficiency of FA in improving the resistance to sulfate solution attack varied according to the type of cation, Na + or Mg2 + in sulfate solutions resulting formation of ettringite or gypsum. The replacement of cement by FA could not effectively prevent acid-type deterioration involving scaling and softening of the mortar in a very low pH of 2 % H_2SO_4 solution. The sulfate-generated expansion of FA mixes was reduced when the FA replacement percentage was more than 30 % when exposed to a 10 % Na_2SO_4 solution. However, when exposed to a 10 % $MgSO_4$ solution, higher FA replacement was not always effective in preventing the magnesium-ion attack because CSH gel produced during the pozzolanic reaction was more susceptible to the magnesium-ion attack.

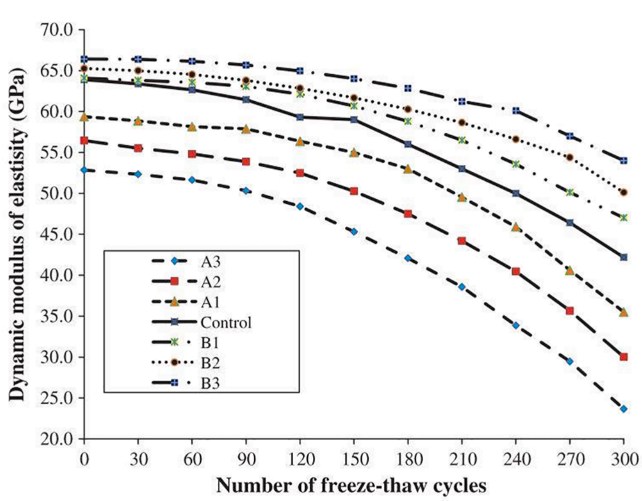

Fig. 30. Dynamic modulus of elasticity – number of F-T cycles of RCC mixtures. Series A cement replacement, series B aggregate replacement with FA (1, 2, and 3 stands for 20%, 40%, and 60% FA) (Mardani-Aghabaglou et al., 2013).

When FA content increased from 0 to 70 %, Aydin et al. (Aydin et al., 2007) observed a decrease in the percentage of strength loss in the 60 days of steam-cured samples from 58 to 21 %, indicating an improved acid resistance in FA concrete. However, no difference in strength loss was observed in samples in standard curing when FA content increased. The study also observed a similar trend in weight loss. According to Verma et al. (Verma, 2013) also, FA had proven to be a useful material for making concrete in aggressive environments, as the study observed a lower loss, compared to plain concrete, in CS in HVFAC with 50 % FA in 0.1 N and 0.2 N concentration sulphuric acid exposure conditions. The improvement in acid resistance of FA concrete is attributed to the additional formation of CSH due to the pozzolanic reaction between FA and CH liberated during the hydration process (Aydin et al., 2007). In another study (Sathyan and Anand, 2019), concrete with only 25 % FA and PCE-based SP performed better against acid attacks than control specimens without SP. However, the difference in a percentage loss of CS between the samples without SP was negligible.

Investigation (Sahoo et al., 2017) on the low carbonated FA concrete revealed that carbonated FA concrete had the highest strength loss in the initial stage of chemical exposure. However, after increasing exposure days, it showed a steeply decreasing rate of strength loss compared to reference concrete and FA concrete. Further, the study observed that the carbonated FA concrete had a higher acid resistance to weight loss when exposed to long periods of water curing and a chemical environment. The benefits of carbonated FA concrete can be explained by the fact that it contains less free lime making it less susceptible to attack by sulfate ions.

Concrete containing 25 % FA modified with TiO_2 and $CaCO_3$ nanoparticles exhibited a greater resistance against the sulphuric acid environment (Uthaman, 2018). This is attributed to the filling effect of nanoparticles, which resulted in a more dense and impermeable concrete microstructure and the formation of more nucleation sites for CSH formation in the presence of nanoparticles (Abhilash et al., 2021; He and Shi, 2008).

Fracture behavior of FA admixed concrete

Fracture energy (G_F), critical stress intensity factor (K_{IC}), fracture process zone, and critical crack tip opening displacement (CTODC) are the factors that influence the concrete's fracture behavior (Abhilash et al., 2021). Lam et al. (Lam et al., 1998) found that a high volume of FA replaced with cement improved the fracture properties of concrete. The study revealed that replacing 45 to 55 % FA in concrete resulted in larger crack tip opening displacement (COD_C) and the mid-span deflection (δc) that subsequently led to K_{IC} and G_F values comparable to or higher than plain cement concrete.

A parametric experimental study (Zhang et al., 2012) on the effect of FA on fracture properties of HPC showed a significant improvement in G_F, K_{IC}, effective crack length (a_c), $CTOD_C$, and maximum crack opening displacement ($CMOD_{max}$) as FA contents increased from 10 % to 20 %. However, these parameters deteriorated as FA levels exceeded 20 % but remained higher than the control sample. The relationship between vertical load (Pv) and δc, CMOD, and CTOD revealed enhanced resistance to crack propagation as FA content increased.

Golewski (Golewski, 2019) also reported high K_{IC} at 20 % FA addition and low K_{IC} at 30 % FA level. According to Golewski the MTS method showed a 2.90 and 3.70 % increase in K_{IC} and $CTOD_C$ at 20 % FA addition, while the Digital Image Correlation (DIC) method showed a

3.50 and 4.20 % increase. However, with 30 % FA substitution, the MTS method observed a 12.20 and 13.2 % reduction in K_{IC} and $CTOD_C$, while the DIC method observed an 11.60 and 12.60 % reduction.

According to mode II fracture analysis (Golewski and Sadowski, 2012; Golewski, 2021), up to 14 days curing age, FA admixed concrete stress intensity factor (K_{IIc}), and unit work of failure (J_{IIc}) remained lower than the control sample. However, after 14 days, K_{IIc} and J_{IIc} were higher at 20 % FA concrete and lower at 30 % FA concrete compared to the control sample, as shown in Fig. 31. After 90 days of curing, mode III fracture analysis found higher stress intensity factors (K_{IIIc}) in 10 %, 20 %, and 30 % FA admixed concrete compared to the reference concrete (Golewski and Sadowski, 2016; Golewski, 2018).

Wong et al. (Wong et al., 2000) found that replacing cement with 15 to 25 % FA had no significant effect on the fracture toughness of mortar at the ages of 28 and 90 days and that higher replacement levels of 45 to 55 % FA adversely affected fracture toughness of mortar. However, the tests conducted on the beam revealed the 15 % FA concrete had the highest value of interfacial (mortar-aggregate interface) toughness at 28 and 90 days, while the G_F increased as FA content increased up to a total of 55 %. Taylor and Tait (Taylor and Tait, 1999) reported a general increase in toughness at 7 and 28 days when FA content increased in mortar, but there was little or no effect at 90 and 180 days. The study suggested that the large FA particles, even after reaction, may not have bonded well with the paste, creating round flaws that affected toughness.

Tang and Lo (Tang and Lo, 2009) reported that incorporating FA in concrete enhanced G_F in NSC and HSC; however, GF of FA admixed concrete significantly improved at a higher temperature range from 400 to 600 °C. In comparison to control concretes, FA concretes had fewer and narrower micro-cracks at the transition zone. It was further stated that the degree of thermal incompatibility between hydrated cement paste and aggregate in high-temperature conditions was minimized by tobermorite production and the tight packing of FA particles at the aggregate-cement paste interface. A recent study by Yousuf et al. (Al-Yousuf et al., 2021) reported a reduction of 22.22 and 5.49 % in G_F with 25 % FA substitution for HSC at 18 h and 28 days, while the reduction was 55.55 and 8.79 % with 50 % GGBS substitution compared to the reference concrete. As concrete's CS and age increased, so did G_F, and for specimens with the same CS, the G_F of HSC was higher than that of NSC.

Zhang's investigation (Zhang, 1995) led him to conclude that cement replacement with HVFA enhanced the fracture properties of concrete. This can be understood by referring to Zhang's model for HVFA cement paste. Zhang's model considers HVFA cement paste a multiphase composite material. It is possible that the unreacted FA particles in the paste will act as microaggregates. These microaggregates will have a greater modulus of elasticity, which will improve the resistance to propagation of cracks. Additionally, cracking around the FA particles causes a greater amount of energy to be lost before the concrete fails. Because of these characteristics, the process of HVFA concrete fracture is less linear, making the material tougher.

Heat of hydration in FA admixed concrete

Several studies (Zhang et al., 2002; Amnadnua et al., 2013; Han et al., 2014) have revealed the decreasing trend of hydration heat as the FA level increases. The increased pozzolan content generally leads to a long dormant period (Ardoğa et al., 2019). The effect of FA on the hydration of the cement include the dilution effect, filler effect, and chemical effect (Xu et al., 2017; Wang and Lee, 2010). A detailed examination of hydration and CS on FA concrete with limestone by Thongsanitgarn et al. (Thongsanitgarn et al., 2014) showed that the heat of hydration of cement having 30 % FA was prolonged and reduced, compared to OPC concrete, due to the cement dilution effect (Wang and Lee, 2010) and FA's delayed pozzolanic response. Increasing pozzolan decreased lime content and increased silica content (Ardoğa et al., 2019). Therefore, inadequate CH to interact with the silica from the FA caused the sluggish pozzolanic reaction at an early age. As a result, the pozzolanic reaction took a longer time to complete. However, FA combined with limestone enhanced the rate of hydration compared to paste containing only FA at the same replacement level, and the hydration rate accelerated as LS concentration increased (Thongsanitgarn et al., 2014). This is because tiny LS particles may provide an extra surface for the nucleation and development of hydration products (Bonavetti et al., 2001), and lead to a possible interaction between FA and LS. A comparative study (Xu et al., 2020) of type I (SSA-380 m^2/kg) and type II FA (SSA-310 m^2/kg) revealed that the physical properties and chemical activities of the admixtures influenced the hydration process. In the study, the type I FA admixed concrete exhibited a higher rate of hydration than type II FA admixed concrete. The larger FA particles exhibited less reactivity than the smaller ones, especially at an early age, resulting in poor bonding between the larger FA particles and the rest of the CSH gel (Taylor and Tait, 1999). This is in line with the findings of (Chindaprasirt et al., 2007) as this study reported increased hydration and pozzolanic reactions in FA of finer particles.

According to (Rong et al., 2014), FA delayed hydration primarily in the dormant and acceleration phases, as seen in Fig. 32. The heat flow peak of the FA mixture occurs significantly later than that of ordinary cement. This is consistent with (Langan et al., 2002) as the study observed that the heat of hydration rate of FA mixes exceeds that of plain

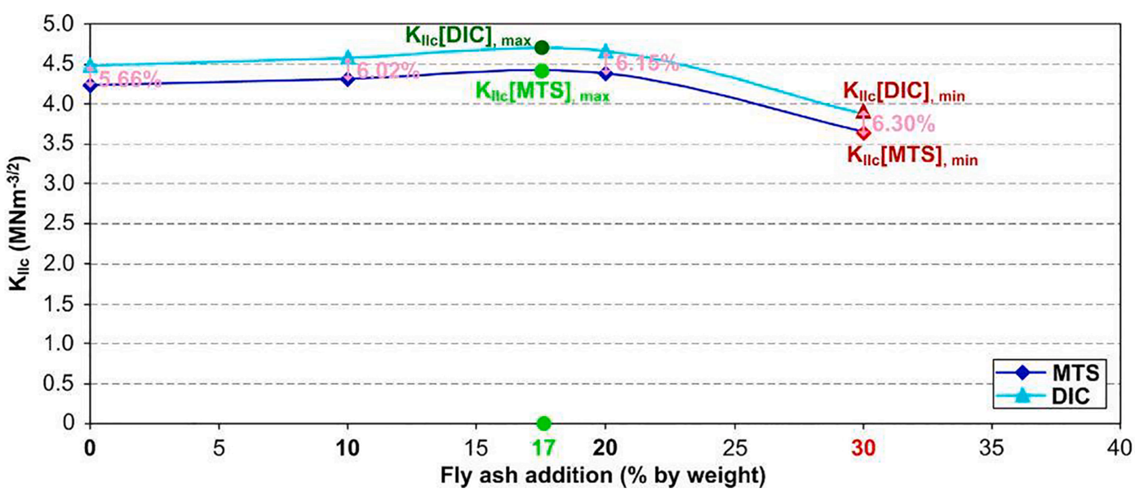

Fig. 31. Dependence of KIIc from FA replacement (Golewski, 2021).

cement at around 8.0 h, 8.5 h, and 9.5 h, respectively, at 0.35, 0.40, and 0.50 w/b ratios, at the end of the acceleration phase. A higher w/c ratio resulted in a greater retardation effect. Due to the increase in water, the concentration of calcium in the pore solution was reduced during the dormant period, and as a result, the dormant period was prolonged. The study cited that FA lowered calcium concentration in the first hour and slowed CH and CSH nucleation and crystallization, which delayed hydration.

FA generally slowed down the heat evolution process at its high replacement level due to the slow pozzolanic reaction rate. At 5 % FA substitution, the heat evolution curve and heat output remained nearly unchanged; the FA particles likely play a nucleating agent for the hydration products, and at FA substitution greater than 30 %, the hydration process was severely retarded (elongated induction period) (Nocuń-Wczelik, 2001). Poon et al. (Poon et al., 2000) reported that, at 25 %, FA substitution resulted in only a 16 % decline in the cumulative heat evolution, and a 45 % FA substitution resulted in a 36 % decline in the cumulative heat evolution. According to Medepalli et al. (Medepalli et al., 2020), Blaine fineness, reactive silica content, and alumina content of FA were closely associated with hydration kinetics and CS development.

Microstructure of FA admixed cement paste and concrete

According to SEM analysis by Saha (Saha, 2018), ettringite needles formed on the surface of the FA particles and in the vacant spaces in the F40 concrete mix after 28 days of curing. The study found that spherical FA particles still existed in the concrete microstructure after 28 days of curing, suggesting that they did not react with the cement during the early stages of hydration. When exposed to the aggressive environment, the FA spherical particles decomposed due to the pozzolanic reaction and were replaced by ettringite needles in the void space between the aggregates. This resulted in a denser binder mix than conventional concrete. According to Hashmi et al. (Hashmi et al., 2021) the microstructures of plain concrete and concrete with 25 % FA were similar. However, However, the plain concrete had a higher amount of ettringite and CH, which led to the development of early strength in the plain concrete. They observed that the presence of FA in the concrete caused more CSH gels to develop due to the chemical reaction between CH and silica, but the amount of ettringite was reduced, resulting in a poor bond and lower strength in HVFA. Plain concrete also featured fewer spaces and cracks, resulting in strong bonding between the aggregates by CH and CSH gel.

Uthaman et al. (Uthaman, 2018) performed various microstructural analyses on nanophase-modified concrete. FA concrete modified with nano-TiO_2 and $CaCO_3$ (FATC) showed resistance to sulfate attack, as the delayed formation of ettringite was observed on the surface of FATC. SEM micrographs of the nano-phase modified FA concrete surface revealed the least formation of calcium sulfate crystals, indicating the least degradation. XRD patterns of FATC concrete surfaces exposed to seawater retained all hydration product peaks after one month, indicating no calcium leaching. The elemental mapping of the FATC concrete surface revealed a low calcium silicon (c/s) ratio, indicating minimal calcium leaching. FATC concrete, an eco-friendly green concrete, proved superior, based on different microstructural analyses, with excellent resistance to sulfate attack and calcium leaching.

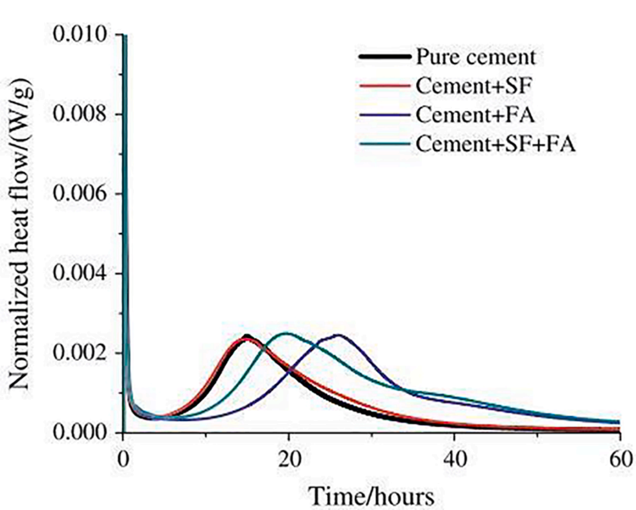

Fig. 32. Heat evolution of cement-based materials at w/b of 0.17. (Rong et al., 2014).

SEM analysis on FA (10 %) and silpozz (20 %) concrete showed the presence of CSH in the form of bright and dark matter in between the aggregates and acting as a binder which improved the mechanical properties of the concrete (Jena and Panda, 2018). The analysis observed the salt accumulation as white spots along with voids and pores. CHS gels were formed over time during the hardening process, and voids were eliminated, resulting in increased strength, and the findings are consistent with (Xu et al., 2020). However, the samples cured in seawater (SWC) after 28 days of normal water curing (NWC) showed no signs of CSH formation in their microstructure, but salt accumulation was observed in some locations as white spots along with voids, resulting in deterioration over time. It has been demonstrated (Sadrmomtazi et al., 2018) that the concrete containing pozzolan (FA and SF) exhibited greater uniformity, compactness, and improved ITZ. According to Taylor et al. (Taylor and Tait, 1999) many voids were observed in the cement paste at the early ages in FA admixed samples, but the number and size of the voids decreased as hydration progressed. The large FA particles did not bond well with the paste, resulting in round flaws that negatively affected toughness. A significant amount of FA particles were found even in well-hydrated concrete. In FA-admixed concrete, Tang and Lo (Tang and Lo, 2009) observed relatively low microcracks at the ITZ due to the formation of tobermorite, a strong hydration product at high pressure and temperature, and due to dense FA particle packing. Furthermore, FA concrete improved micro-crack resistance at low and high temperatures, making concrete much tougher. The XRD results revealed a significant reduction in $Ca(OH)_2$ intensity in cement paste with finer FA when compared to cement paste with coarser FA, and according to the SEM analysis, the cement paste with finer FA had a denser structure in cement paste than the paste with coarser FA (Chindaprasirt et al., 2007).

Other influencing factors of properties of FA concrete

Fineness and type of FA

It was observed by Medepalli et al. (Medepalli et al., 2020) that Blaine's fineness had a significant influence on the development of CS than the reactive silica and alumina content of FA. Furthermore, the experimental investigation revealed that as the fineness of FA increased, so did the CS of the mix, as shown in Fig. 33.

According to Yazici and Arel (Yazici and Arel, 2012) the highest values of CS and STS in concrete were obtained when the cement was replaced with 5 % finest FA of Blaine fineness 5239 cm^2/g as compared to the concrete with FA of Blane fineness 2351 cm^2/g and 3849 cm^2/g as well as with FA replacement levels of 10 and 15 % as shown in Fig. 34. In the study, the fineness of FA had a positive effect on the mechanical properties of the concrete only when the Blaine fineness value exceeded 3849 cm^2/g. Furthermore, at all curing ages upto180 days, the rate of strength gain is greater than the control samples when FA fineness was 5239 cm^2/g, and the percentage replacement was 5 %.

Chindaprasirt et al. (Chindaprasirt et al., 2007) investigated the influence of FA fineness on cement pastes at 20 and 40 % replacement levels. In the study, FA of type F was ground and classified into two fineness types, the original FA of 19.1 μm particle size and the classified

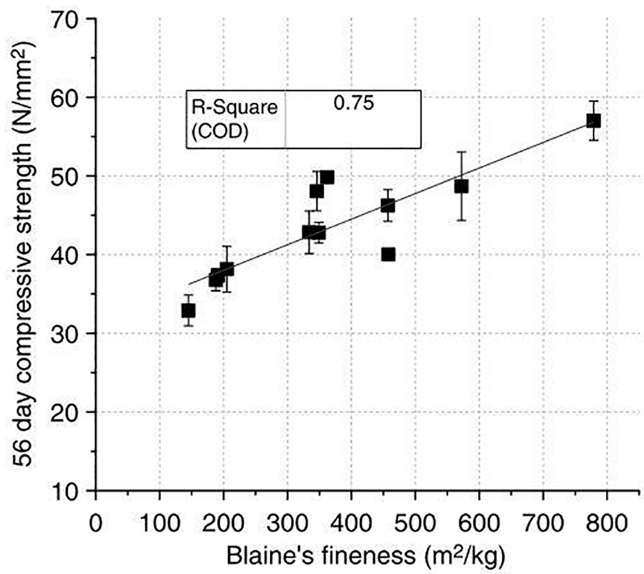

Fig. 33. Correlation between Blaine's fineness of FA and CS of mortar (Medepalli et al., 2020).

FA of 6.4 μm particle size. Up to 90 days, the cement paste with classified FA produced higher CS than that with original FA but lower than that of the control paste without FA. This is consistent with the findings of Moghaddam et al. (Moghaddam et al., 2019). The study also reported that adding classified FA caused a decrease in total porosity, capillary pores, and average pore size while increasing gel pores. Finer classified FA particles also improved hydration reaction, pozzolanic activities, packing, and nucleation effects, resulting in a paste with a more homogeneous and denser structure with lower CH, due to increased consumption of CH, compared to the paste with coarser FA (Chindaprasirt et al., 2007). Another study on mortar by Chindaprasirt et al. (Chindaprasirt et al., 2004) examined the effect of 40 % FA with Blaine finenesses of 1800 cm^2/g, 3000 cm^2/g, 3900 cm^2/g, 4800 cm^2/g, 4900 cm^2/g, and 9300 cm^2/g. It was observed that the mortar with the finest FA had the highest pozzolanic activity and, consequently, the highest CS, which increased with increasing fineness. Fine FA mortars with a low w/b ratio had a low drying shrinkage, while coarse FA mortars with a high w/b ratio showed relatively high drying shrinkage, indicating the importance of the w/b ratio on drying shrinkage. However, the study found that when immersed in sulfuric acid solution, mortar samples with coarser FA had greater resistance to sulfate attack because courser FA particles with rougher surface had a better bond with the cement matrix and occupied more volumes, thus reducing the volume of OPC that resulted in higher resistance to sulfate attack. Since the coarse FA was used in high volumes, the SCC mixtures lost significant strength (Sahmaran and Yaman, 2007).

According to Moghaddam et al. (Moghaddam et al., 2019) the rapid pozzolanic reaction in the cement paste containing finer FA resulted in increased CH consumption and the formation of additional CSH gel, which caused a denser microstructure of the system compared to the paste containing coarser FA and thus increased CS. Additionally, in the isothermal calorimetry analysis done for the heat of hydration evolution, the heat of hydration decreased with FA replacement. This may be attributed to the lower solubility index of FA in the blended paste. Another reason for the lower heat of hydration could be less availability of C3S with the increased FA content. However, at the same percentage of FA replacement, the hydration heat was higher with higher fineness values, which the study suggests was due to the higher surface area of FA particles. Further analysis of the flowability of the cement paste showed a marginal increase in the flow in the paste with finer FA. This was attributed to the spherical shape and smooth glassy surface texture of FA particles.

Choi et al. (Choi et al., 2012) suggested that incorporating fine FA into cement mortar mixes could help reduce temperature rise and setting time retardation while also improving the strength properties of the mortar. The finer the FA particles, the faster the paste will set due to the packing effect of fine FA particles in mortar mixes. The study also reported a higher CS, after 28 days, in the mortar with higher Blaine fineness of 9632 cm^2/g compared to the mortars with a fineness of 4125 cm^2/g, 6686 cm^2/g. However, the tensile and FSs were always high in finer FA mortars at all ages up to 56 days at all FA replacement levels of 15, 30, 45, and 60 %. The improved compressive and TSs with improved microstructure in concrete with finer FA, at 30 % dosage, were also reported (Southararajan and Sivakumar, 2012).

Naganathan and Linda (Naganathan and Linda, 2013) studied the effect of FA fineness on water absorption, sorption, and CS. In this study, two types of FA with different fineness values of 6477.93 cm^2/g and 10703.54 cm^2/g were considered at different replacement dosages of 10, 20, 30, and 40 %. The study reported an increase in CS with the increase in FA fineness after 28 days due to the high pozzolanic activity or pozzolanicity of the finer FA particles as observed by (Chindaprasirt et al., 2007; Chindaprasirt et al., 2004; Southararajan and Sivakumar, 2012). With increasing FA fineness and dosage, the absorption and sorption decreased as the finer FA particles filled the voids and increased

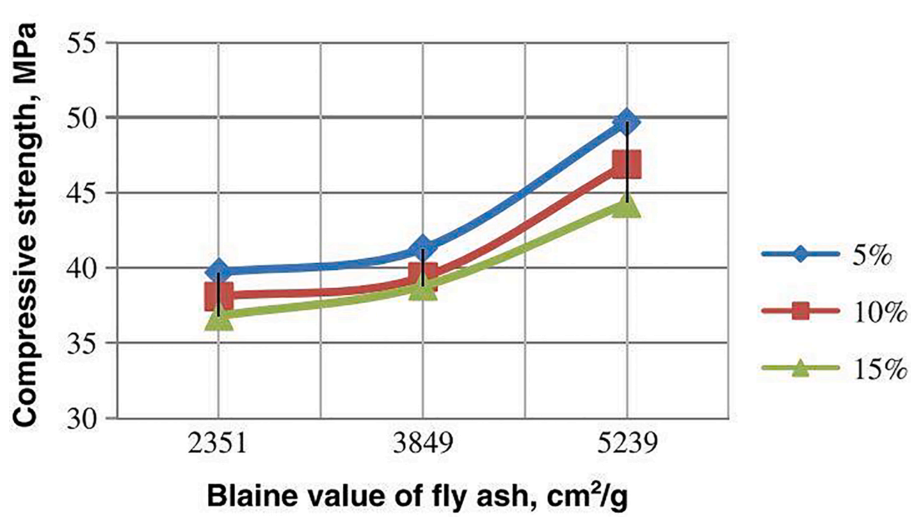

Fig. 34. 28-days CS of concrete vs the fineness of FA concrete (Yazici and Arel, 2012).

the system's density, conforming to (Chindaprasirt et al., 2007; Chindaprasirt et al., 2005).

Temperature

SEM analysis (Fan et al., 2019) revealed some unreacted FA particles at 20 °C, but when the temperature increased to 450 °C, all unreacted particles vanished due to FA and calcium hydroxide (CH) reaction. Finally, as the temperature approached 700 °C, the CSH phase decomposed, and the cement matrix turned into a porous and weak, loose white substance, as observed by Peng and Huang (Peng and Huang, 2008) causing the mechanical properties of the concrete to deteriorate.

Tang and Lo (Tang and Lo, 2009) observed that when the temperature increased from 27 to 200 °C, the CS slightly increased in FA admixed normal and high strength concretes (NSC and HSC); however, beyond 200oC, the strength started to decrease. As the temperature rose from 27 to 400, 500, and 600 °C, the CS reduced by 29, 43, 63 %, TS by 39, 54, and 72 %, and MoE by 58,77 and 87 %, respectively. However, the fracture energy (G_F) increased by 31, 64, and 75 %. It was found that the NSC and HSC admixed with FA performed better at elevated temperatures than unadmixed concrete.

The fractures in the RAC specimen grew significantly as the temperature increased, according to Ren et al. (Ren et al., 2019). On the other hand, it was observed that the number of fractures in the specimen decreased as the FA level increased. In all types of samples, the weight loss also increased with increased temperature. The study reported that the rate of weight loss might be slowed down by adding FA. The decrease in the rate of weight loss was especially noticeable in RAC containing 50 % FA after exposure at 600 °C. Furthermore, when the temperature raised from 20 to 400 °C, the rate of loss of strength of concrete at 0 %, 20 %, and 50 % FA dosage was 0.42, 0.27, and 0.16, respectively. This indicated that FA effectively checked the strength loss of RAC exposed to high temperatures.

Case studies

A summary of fly ash concrete case studies from the American Coal Ash Association (ACAA) is given below.

Sl. No	Project	Place and country	Completion year	Project details	FA used	Benefit of FA admixed concrete/ remarks
1	1144 fifteenth street	Denver, Colorado, U.S.	2018	42-story, 603- foot high building, 640,000 sq. feet office space	40 %	• Reduced the heat of hydration in mass concrete with a volume of about 1800 m^3 • Slowed the initial curing process • Preserved the strength and quality of concrete • Minimised the cement and concrete required for the foundation • Reduced the overall cost while increasing the strength
2	Apogee stadium	Denton, Texas, U.S.	2011	University of North Texas stadium	35%	• A carbon offset equivalent to the stadium's electricity production for three years was achieved. • Obtained the highest level of LEED certification awarded by the U.S. Green Building Council.
3	BAPS Hindu Mandir	Abu Dhabi, UAE	2022	BAPS Shri Swaminarayan mandir 3000- cubic meter concrete in foundation mat	55%	• FA admixed concrete to construct the foundation mat to uphold the temple's heavy masonry • Single placement of 3000 m^3, one of the largest ever single concrete placements in UAE • Reduced heat of hydration • Minimised the thermal crack
4	Burj Khalifa	Dubai, UAE	2010	163 floors concrete multi-use tower, 2717 feet height, 465,000 square foot building	25% FA and 7% SF for pile 40% FA for the raft	• Reduced peak temperatures and the likelihood of cracking during mass placements in the arid climate. • FA admixed high-performance concrete used for the construction as the sub-structure sits in an extremely corrosive environment with high chloride and sulfate concentration of 4.5 and 0.6%, respectively
5	Calgary International airport runway and tunnel	Calgary, Alberta, Canada	2014	Airport runway and concrete traffic tunnel under the new runway	15%	• Life cycle cost and the durability of the structure were the major consideration for the design of a structure with 400,000 $m^3$of concrete
6	Capital/Bank of America tower	Houston, Texas, U.S.	2019	The 35-story tower, 750,000 square feet of office	55%	• The addition of FA resulted in a 33% reduction in the production of ozone-depleting compound • 19% reduction in global warming potential • 12% reduction in acidification • Saved one million pounds of CO_2 • High FA dosage reduced the heat of hydration • Minimized the thermal cracks
7	DFW connector	Dallas, Texas, U. S.	2014	4 highways, 2 major interchanges, and 5 intersection bridges	25%(Class F FA)	• FA admixed concrete used for temperature control, workability improvement, and to mitigate ASR and sulfate attack.

(continued on next page)

(*continued*)

Sl. No	Project	Place and country	Completion year	Project details	FA used	Benefit of FA admixed concrete/ remarks
8	Dover Air Force Base Runway Project	Dover, Delaware, U.S.	2016	US air force runway	Thermally refined class F FA	• A renovation work to extend life span an additional 50 to 75 years
9	Gautrain	Gauteng, South Africa	2012	50-mile-long, a high-speed commuter rail line	30-35%	• 28 million cubic feet of concrete with a life expectancy of 100 years • Reduce the cost of construction, environmentally friendly, and higher strength than pure cement mix. • Compressive strength exceeded 27.6 MPa within 24 hours and averaged 73.8 MPa after 28 days. • In foundation, FA is used with bentonite to provide good pumpability
10	Global Change Institute Building	Brisbane, Australia	2013	GIC headquarters is a four-story building comprising three suspended concrete floors made from 33 precast geopolymer concrete panels	Geopolymer concrete (Class F FA and GGBS, no cement)	• Emissions reductions of 80-90% • 30% higher flexural strength • High sulfate, acid, and chloride ion ingress resistance • Low shrinkage • Low heat of hydration
11	Georgia Port Authority Mobile Gantry Crane Runway	Savannah, Georgia	2012	In 2012, the Georgia Port Authority undertook reconstruction of a failing portion of the concrete runways which are subjected to 56 tonnes	Class C FA	• Class C fly ash to help improved the performance characteristics of concrete over many traditional cement concretes • Improved volume stability, corrosion resistance, scaling and sulfate resistance, and immunity to ASR • Less heat of hydration • Minimized thermal cracking
12	Hoover Dam Bypass	Mohave County, Arizona, U.S.	2010	Concrete arch bridge	20% (Class F FA)	• Very low w/c ratio of 0.31 • Achieved 28 Mpa in one day and 83 MPa in 56 days • Low heat of hydration
13	I-35W Saint Anthony Falls Bridge	Minneapolis, Minnesota, U.S.	2008	Concrete bridge, Footings, drilled shafts, piers and superstructure	Superstructure- 25% FA Footing and drilled shaft- 18% FA Piers- 16% FA	• Designed for a 100-year life • 3800 m^3 concrete • High strength • Frost resistance
14	J. Craig Venter Institute	La Jolla, California, U.S.	2013	Three-story, 45,000-square foot laboratory facility	30%	• Environmentally sustainable concrete • Aesthetic quality • LEED platinum standards
15	Medupi Power Station	Lephalale, South Africa	2020			• Temperature control in mass concrete placement • Met specific shrinkage standards • Less permeable concrete • Dense structure • Resisting abrasion and chemical ingress
16	Niagara Region Wind Farm	Niagara, Ontario, Canada	2016	Concrete towers for 77 wind turbines spread out over a 170-square-mile area in south- east Ontario. Collectively, the turbines, each 425 feet high, utilized 2.6 million cubic feet of ready-mix concrete and 1.3 million cubic feet of precast concrete	50%	• Low heat of hydration • Temperature control • High strength • Low mixture cost • Thermal cracking
17	Oroville Dam Spillway Recovery	Oroville, Butte County, California, U.S.	Phase 1: 2018	Earth-filled embankment dam on the Feather River near Oroville	50% Class F FA	• Low heat of hydration • Less thermal cracking
18	Saluda Dam	Columbia, South Carolina, U.S.	2005	Roller compacted concrete (RCC) gravity dam downstream of the dam.	50%	• Improved workability • Reduce heat of hydration
19	San Francisco-Oakland Bay Bridge Eastern Span	Oakland, California, U.S.	2013	San Francisco-Oakland Bay Bridge of 4.5 miles	Footings- 50% FA Columns- 40% FA	• Improved workability • Reduced heat of hydration • Reduced thermal crack • Mitigated ASR • Improved corrosion resistance • 150 years of service life
20	Transbay Block 9 Residential Tower	San Francisco, California, U.S.	2019	42-story residential tower	40%	• Environmentally sustainable concrete • Improved workability
21	University of Minnesota Recreation Center Expansion	Minnesota, U.S.	2013	HVFA concrete was used extensively to strengthen the structural elements of the remodelled facility of UMN's recreation centre as well as for its aesthetic appeal as an exposed material	30%	• Enhanced workability • High strength • Enhanced durability • Lower cost
22	W Philadelphia Hotel	Philadelphia, Pennsylvania	2018	Nine-foot-thick foundation covered 20,000 square feet and contained 25.2 million pounds of concrete.	50%	• Slowed down the hydration process thus reduced generation oh heat at the core concrete

Conclusion

Producing cement is energy-intensive and emits a large amount of CO_2. Waste products like FA can be used as an alternative to cement, thereby minimizing cement consumption, and thus, FA can be beneficial both environmentally and economically. The promising results of substituting a small percentage of FA with cement propels HVFAC research to new heights. Furthermore, such a high utilization of FA is vital for sustainable development because waste resources may be utilized as efficiently as feasible.

The FA makes the concrete more workable. Smooth FA particles, due to their spherical shape, act as miniature ball bearings in the concrete, giving a lubricating effect, thus reducing the viscosity of the concrete. This effect also decreases frictional losses during concrete pumping.

FA particles adsorb on the surfaces of oppositely charged cement particles, preventing them from flocculating. As a result, a large amount of water is released, thus lowering the water demand for particular workability. Therefore, in concrete, replacing cement with FA reduces water demand for the same slump, and increasing FA levels may reduce water demand hence the presence of FA can minimize the requirement for SP.

FA is a pozzolanic substance that forms CSH gel, which is the main binder in cement and concrete and is responsible for their strength when it reacts with CH produced by cement hydration. Further, combining FA with the lime formed during cement hydration produces additional strength. Thus, FA concrete will have lower strength at early curing ages and higher strength at later curing ages than cement only concrete. The content of FA, its chemical composition, the fineness of FA particles, as well as their surface area, water to binder ratio, and temperature are all factors that influence the concrete's strength.

The increase in compressive strength at a certain FA dose can be explained by the fact that the optimal dosage of FA is necessary to completely fill the pores that are present within the concrete. The addition of finer cementitious particles accelerates the pozzolanic reaction with CH. Hence combining FA with SF or GGBS can improve the strength properties of FA admixed concrete.

Concrete with typical design strength can be produced with high FA levels, and the early strength issues associated with such HVFC can be addressed by the use of FA with rapid hardening cement or low energy clinker.

FA increases the hydration process over time, resulting in an enhanced ITZ density and microstructure as the pore structure gradually gets more refined with curing time. The increase in density may contribute to an increase in concrete strength, while the decrease in pore network connectivity results from the refined pore structure may minimize transport processes and contribute to improvement in concrete durability.

The amount of FA present in the concrete has an effect on the sorptivity, water permeability, voids that are permeable to water, and water absorption of the concrete. When the FA content increased up to a certain level, these properties were reduced, but they increased at higher levels of FA content. The additional CSH gel that formed as a result of the pozzolanic activity of the FA particles occupied the concrete pores. This caused the concrete to become dense and compact, which led to a reduction in the permeability coefficient.

Carbonation resistance decreases as the FA content increases and is mainly dependent on the compressive strength of the concrete, FA concentration and, to a lesser degree, the moist-curing period than with the type of FA used. On the other hand, the combination of RCA and FA is more effective at preventing the carbonation of concrete with RCA concrete.

FA concrete can perform better against chloride, sulfate and acid attacks as the pozzolanic reactions reduce the quantity of CH and increase CSH gel which refines the ITZ and matrix pores and lowers the permeability. The decreased chloride ion permeability in FA concrete improves its corrosion resistance.

By incorporating FA, concrete becomes more ASR resistant because the FA reaction consumes alkali, thereby reducing their availability for expansive reactions with reactive aggregates. The ability of FA to reduce the availability of alkali and hydroxyl ions in the solution depends on the chemical composition and particle size of FA. Therefore, different FAs have different safe replacement levels.

FA concrete may function far better at higher temperatures than regular concrete. This is because, at higher temperatures, all the unreacted FA particles react with CH to produce more CSH. FA concrete may also limit the weight loss of concrete at elevated temperatures; this indicates that FA concrete can effectively check the strength loss of concrete which is subjected to high temperatures.

According to Zhang's model, the unreacted FA particles in the paste may act as micro-aggregates with a higher modulus of elasticity, which increases the resistance to crack propagation. The cracking around the FA particles results in more energy to be dissipated before failure. With these features, the fracture process of HVFA concrete becomes less linear, and the material becomes tougher.

A decreasing trend of hydration heat can be observed in FA concrete. The heat of hydration decreases with an increase in FA dosage. The low hydration heat is likely due to the reduced solubility index of FA in blended paste and the decreased availability of C3S as FA content increases. Inadequate CH to interact with the silica from the FA causes the sluggish pozzolanic reaction at an early age. FA combined with limestone can enhance the rate of hydration because the tiny LS particles may provide an extra surface for the nucleation and development of hydration products. Blaine fineness, reactive silica content, and alumina content of FA are closely associated with hydration kinetics and compressive strength development.

When exposed to the aggressive environment, the FA spherical particles decompose due to the pozzolanic reaction and are replaced by ettringite needles in the void space between the aggregate, causing a denser binder mix than conventional concrete. FA concrete has a relatively low microcrack at the ITZ due to the formation of tobermorite, a strong hydration product at high pressure and temperature, and due to dense FA particle packing.

Fly ashes are highly heterogenous from its particles size to the chemical composition. It can be seen from the several studies in the past that the properties of the fly ash incorporated concrete are varied according to the type, fineness and chemical composition of the fly ashes. Therefore, it is difficult to arrive a definitive conclusion on the effect of fly ash on concrete. However, the results available from the extensive studies can be considered as guidelines for the further research and the heterogeneity of the fly ash still makes the door opened for the further research on fly ash concrete.

Declaration of Competing Interest

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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