Incorporating Ground Granulated Blast Furnace Slag & Fly Ash in Concrete Production for Sustainable Construction: A Review

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ABSTRACT

Portland cement is the primary source of CO_2 emissions in concrete production due to the energy required for the calcination of limestone, the release of CO_2 from fuel combustion during cement manufacturing, and the hydration process during setting. To mitigate the environmental challenges associated with cement production, the use of industrial waste as cementitious material can significantly reduce both the volume of waste generated and its disposal in landfills, thereby freeing up land for other purposes. Concrete has traditionally incorporated natural pozzolans, waste and recycled materials, and industrial byproducts as partial replacements for Portland cement. Among these, Ground Granulated Blast Furnace Slag (GGBFS) and Fly Ash (FA) are the most commonly used supplementary cementitious materials (SCMs), known for enhancing the mechanical strength, flow ability, and durability of concrete. SCMs improve the concrete matrix's resistance to chemical attacks, reduce permeability, and contribute to long-term strength development.

This review highlights the scientific literature on the feasibility and effectiveness of using GGBFS and FA as sustainable alternatives to cement in mortar and concrete production. GGBFS is a byproduct of the iron-making process, while FA is a fine particulate material generated from coal-fired power plants. In literature there are very limited comprehensive review studies for hybrid use of GGBFS and FA to identify optimal blending ratios, microstructural analysis and mechanical performance trends. Most of the reviews are generic and focus on the individual performance of GGBFS or FA in concrete. This paper presents a detailed discussion of manufacturing processes, physical characteristics, and their impact when used as partial cement replacements in individual and hybrid matrix form. It also summarizes findings from previous studies regarding optimal replacement percentages, which vary depending on the source, mix design, and particle size distribution of the materials. Finally, this review proposes process improvement strategies to optimize the use of GGBFS and FA in future sustainable concrete applications.

Keywords

Ground Granulated Blast Furnace Slag (GGBFS), Fly Ash (FA), Pozzolanic Reaction, Workability, Compressive Strength, Cement Replacement, CO_2 Emissions, Sustainable Concrete

1. INTRODUCTION

Cement is the main constituent of concrete and acts as a binder and provides hardness. However, this is the main element of concrete that makes concrete responsible for adverse impacts on environment, human health and plantation. A large amount of fuel is required during cement manufacturing makes it highly unsustainable material (Gartner and Hirao, 2015; Tangadagi *et al.,* 2020). It is also a major cause of emissions of CO_2 and heavy metals like zinc, sulfides, selenium and galena in air during its manufacturing and hydration processes and hence it is considered as one of the main and fast-growing reasons of global warming (Oh *et al.,* 2014; Zhang *et al.,* 2019). In addition to energy consumption, the clinker producing businesses also emit CO_2 during the carbonization process. Approximately 8% of global carbon dioxide emissions are ascribed to the production process of this hydraulic cement (Elnaz Khankhaje *et al.,* 2024). Acrding to (Fayomi *et al.,* 2019), for every 1-kilogram production of cement, 0.5-0.9 kg of CO_2 is discharged into the atmosphere, evolving in roughly 3.24 billion tons of total CO_2 emissions annually for a total production of 3.6 billion tons of cement. Due to these drawbacks, researchers have been working for decades for the replacement of cement by other pozzolanic materials that can be imparted as full or partial replacement of cement in concrete (Rahla, Mateus and Bragança, 2019; Kaliyavaradhan, Ling and Mo, 2020; Koksal *et al.,* 2023; Akhtar *et al.,* 2022; Saif *et al.,* 2023).

Similarly, solid waste created from construction, mining, municipal, and agricultural industries contributes significantly to pollution and landfills. Population and economic expansion caused by urbanization tend to lead to a rise in waste output, which is responsible for the reduced green space by increasing landfill areas, increased air pollution, and waste accumulation of all environmentally damaging things (Negash *et al.,* 2021). Landfills provide considerable environmental challenges when utilized for industrial waste, encompassing soil, water, and air pollution, the discharge of detrimental greenhouse gases like methane, and the risk of prolonged contamination from leachate and dangerous substances. Landfills necessitate extensive land expanses, posing challenges in regions with constrained space. They can influence the area's appearance and may be unattractive and distasteful to neighboring residents, ultimately leading towards a negative impact on tourism and other sectors in the nearby areas. Therefore, sustainable management of this waste is essential in solving the environmental issue. In terms of sustainability, researchers have numerous opportunities to contribute to the reduction of environmental and socioeconomic repercussions (Hansted *et al.,* 2023; Hansen and Sadeghian, 2020; He *et al.,* 2019; Lancellotti *et al.,* 2015; Zawrah *et al.,* 2016; Singh, 2018). Such possibilities include the creation of novel materials with attributes equivalent or greater to those currently used while having a less environmental imprint.

To mitigate these effects, waste materials are incorporated in construction materials to contribute towards sustainability. Waste materials and by products having pozzolanic activity can be used as cement replacement materials. Manufacturing waste, including GGBFS, silica fume, metakaolin, and FA, can replace OPC and remarkably reduce greenhouse gas emissions and landfill problems as well. To guarantee resource exploitation of solid waste, research is also ongoing on the synergistic use of many solid wastes such as GGBFS, FA and carbide slag (CS), as cementitious materials (Li *et al.,* 2025). As per ASTM Pozzolanic materials are generated when substances including silica, calcium, alumina, magnesia, and iron reach a concentration of over 70% (Pourkhorshidi *et al.,* 2010). GGBFS and FA reaction has a notable impact on the properties and strength development of concrete (Yang *et al.,* 2015). The replacement of GGBFS and FA extends the concrete mixtures' initial and final setting times (Hoang, Tran and Lee, 2024).

1. RESEARCH RATIONALE

This study evaluates the effectiveness of GGBFS and FA as cementitious materials alongside Portland cement by investigating the physical characteristics of GGBFS and FA and their impact on concrete workability and mechanical strength as done by previous research. This research also seeks to investigate the feasibility and effectiveness of using these industrial wastes in terms of sustainability in the construction industry as these waste byproducts can drastically damage adjacent water, air, and land. Instead of being discarded, these materials can benefit both the environment and the economy by being used in concrete production. This review will provide essential information for a better understanding of fresh and hardened properties of concrete incorporated with GGBFS and FA as well as highlights the awareness for the benefits of using these materials for sustainable construction.

2. PRODUCTION

When iron is extracted from iron ore in blast furnaces, GGBFS, a byproduct of the iron and steel industry, is produced. Iron ore and limestone flux are mixed in the blast furnace to produce pig iron. The granulating method includes using high-pressure water jets to cool molten slag. The slag is promptly put out, resulting in granular particles of varying sizes smaller than 5 mm and forms a glassy substance called Granulated Blast Furnace Slag (WANG, P. Z., TRETTIN and RUDERT, 2005). Rapid drop of temperature by cooling prevents the formation of larger crystals, resulting in 95% granular calcium-aluminosilicates that have non-crystalline phase (Mohammadhosseini *et al.,* 2020) and it is ground into a fine powder. GGBFS has been extensively used as an SCM for the last few decades in concrete production because of its ability to enhance the mechanical and durability properties of concrete. The manufacturing process of GGBFS is depicted in the following figure:

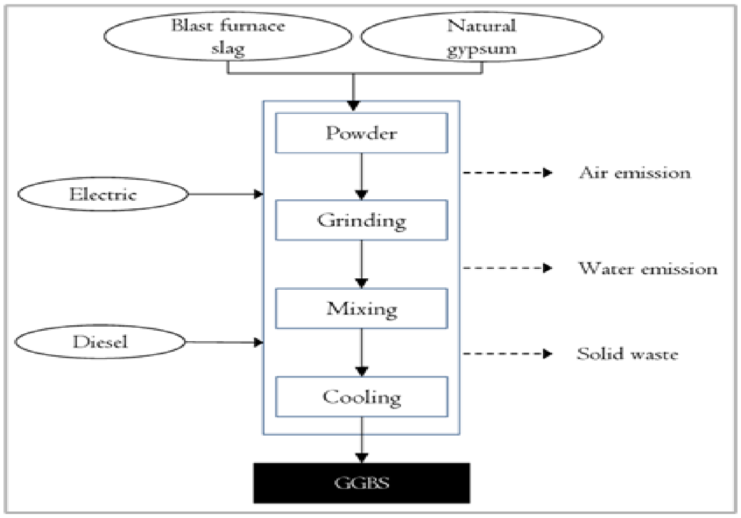

Figure 1: Production of GGBFS (Kim and Chae, 2016)

FA is an additional product obtained as result of coal combustion, and it improves concrete durability and mechanical strength. Thermal power plants are a major source of electricity in different countries. As coal is used to generate more energy, it produces more ash. Around 75-80 percent of the ash produced by power plants is FA. Based on its chemical composition and quarry from where it is obtained, FA is categorized into two types, Class F and Class C (Arrieta Martinez, 2012). Fly ash's finer particles help concrete work more easily, have greater long-term strength, and have less permeability as compared to conventional concrete. Concrete containing class C FA develops strength appreciably more rapidly than the concrete containing class F FA because it contains more calcium (McCarthy and Dyer, 2019). Pulverized coal is injected into the combustion zone of the coal producing furnace, where its flammable ingredients, primarily carbon, hydrogen, and oxygen, erupt and burst into flames at around 1400-1500 °C. Small liquid droplets which are formed when these materials melt are carried out by the flue gases from the burning zone and then they are cooled rapidly, forming minute spherical glass particles. Mechanical and electrical precipitators, also known as baghouses, capture these particles from flue gas. FA has been given the name of fly ash as they are referred to the ash particles which are produced and "fly" away from the furnace along with the flue gases before capturing (Thomas, 2013). The manufacturing process of FA is shown in the following figure:

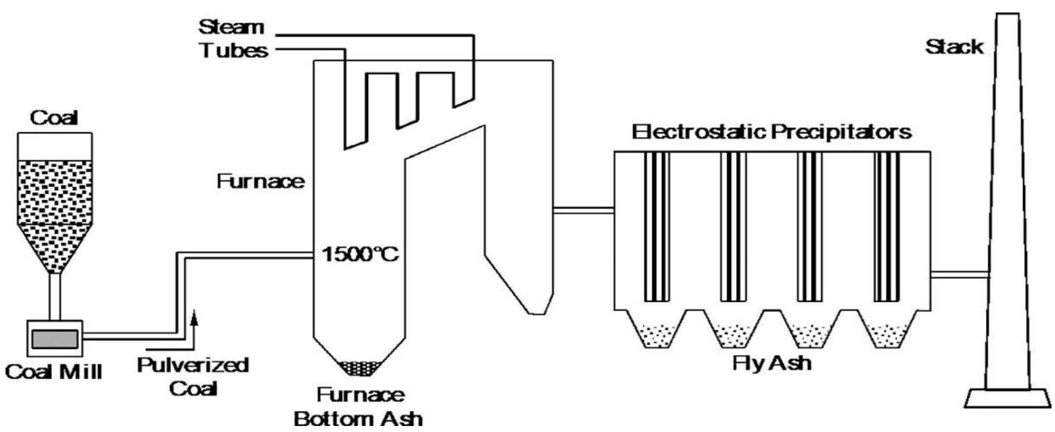

Figure 2: Production of Fly Ash (Thomas, 2013)

3. PHYSICAL PROPERTIES

The physical qualities and distribution characteristics of GGBFS and FA affect their reactivity and strength in comparison to cement and affect their adaptability and capacity to be used as alternative of cement in concrete. The following table shows the physical characteristics of GGBFS and SF used in previous research.

Table 1 Physical Characteristics of GGBFS in previous research

AUTHORS	Specific Gravity	Bulk Density (kg/m^3)	Specific Surface Area (cm^2/g)
(P. *et al.,* 2015)	2.54	1668	-
(Altoubat *et al.,* 2016)	2.90	-	3800
(Patra and Mukharjee, 2017)	2.56	1394	-
(Ramakrishnan *et al.,* 2017)	2.85	-	4000
(Rathod and Hombal, 2017)	2.75	1165	-
(Majhi, R. K., Nayak and Mukharjee, 2018)	2.82	-	5000
(Gholampour and Ozbakkaloglu, 2017)	2.91	-	4500
(Ganesh and Murthy, 2019a)	2.85	-	3960
(Phul *et al.,* 2019)	2.79	-	-
(Mahmoud Elsayed *et al.,* 2022)	2.93	-	4500
(Manjunatha, Seth and Balaji, 2021)	2.9	1200	4500
(Kathirvel and Murali, 2023)	2.85	-	-

Table 2 Physical Characteristics of FA in previous research

AUTHORS	Specific Gravity	Bulk Density (kg/m^3)	Specific Surface Area (cm^2/kg)
(Mugahed Amran *et al.,* 2020)	2.51	-	3652
Jena et al. (Jena and Panda, 2018)	2.12	-	3330
(Phul *et al.,* 2019)	2.43	-	-
(Kumar *et al.,* 2022)	2.12	-	3180
(Rao, S. K., Sravana and Rao, 2016)	2.5	-	3590
(Gholampour and Ozbakkaloglu, 2017)	2.54	-	3900
(Sadrmomtazi, Tahmouresi and Kohani Khoshkbijari, 2018)	2.54	-	3560
(Saha, 2018)	-	-	4300
(Mahmoud Elsayed *et al.,* 2022)	2.47	-	3970
(Shaikh, Faiz Uddin Ahmed and Hosan, 2019)	2.60	-	-
(Nukah *et al.,* 2022)	2.38	-	4200
(Farzad Moghaddam, Vute Sirivivatnanon and Kirk Vessalas, 2019)	2.08		3680
(Das *et al.,* 2022)	2.04	-	4052

Fineness Modulus (FM) estimates the average particle size of a sample. A lower FM (i.e., finer particles) often indicates greater reactivity of GGBFS. Because of the increased reactive surface area, finer GGBFS leads to faster early strength growth. It is influenced by energy-saving and concerns related to economic recovery as well (Mahapatra, Pradhan and Barai, 2021). However, using too fine a substance might increase water demand and reduce workability if not adjusted. Therefore, the fineness of GGBFS should be more than cement or at least equal

(Ogirigbo and Black, 2016). Coarser GGBFS (greater FM) may delay hydration and diminish early strength while still contributing to long-term strength. Lower FM fly ash (finer FA) increases pozzolanic activity, which contributes more to strength (particularly over time), improves workability due to better particle packing and void filling, and improves durability by reducing permeability. On the other hand, higher FM (coarser FA) may behave more as a filler than a pozzolan, resulting in reduced reactivity and workability, ultimately slowing strength increase. Specific Gravity is the ratio of the density of GGBFS/ FA to that of water. GGBFS generally has a specific gravity of 2.8 to 3.0 while 2.1 to 2.6 for FA. A lower specific gravity than Portland cement (typically approximately 3.15) means higher porosity, or the presence of unburned carbon may have a negative impact on workability and strength and can affect mix design calculations. These influences paste volume, workability, and possibly the strength-to-cement ratio. A higher specific gravity is typically associated with denser, more effective pozzolanic materials that contribute more to concrete density and strength. A thorough understanding of specific gravity is required for appropriate proportioning and batching. Surface Area, also known as Blaine Fineness, is a measure of particle fineness (usually in m^2/kg) that indicates a more reactive surface for pozzolanic reaction. Increased surface area boosts responsiveness, which improves both early and late strength development and improves pozzolanic processes, which help to utilize calcium hydroxide to generate more gel in the form of calcium-silicate-hydrate (C-S-H), resulting in increased durability. It can enhance sulphate and chloride ion resistance while decreasing permeability. However, if not maintained properly, a large surface area can increase water consumption and cause slower setting times. Lower surface area indicates slower reaction and fewer pozzolanic activity but may increase workability slightly due to lower water demand. Table 3 provides a summary of how variations in key physical properties of GGBFS and FA impact concrete performance, particularly strength development (Ahmad *et al.*, 2021; Łukowski and Salih, 2015; Farzad Moghaddam, Vute Sirivivatnanon and Kirk Vessalas, 2019).

Table 3 Essential physical properties for strength development in concrete

PROPERTY	High Value	Low Value
Fineness Modulus	Coarser Particle, Slow Reactivity and Lower Early Strength	Fine Particle, better for strength and reactivity
Specific Gravity	Denser Material gives more strength, affects the mix proportion	Makes porous, affects the quality and decreases the strength
Surface Area	Increase the interaction with water, reduce porosity and ultimately lead to an increase in pozzolanic reaction and better strength but may require admixture for workability.	Less reactivity, less strength, more pores.

Scanning Electron Microscopy (SEM) is a strong tool for studying the microstructure and morphology of GGBFS and FA. Under SEM, GGBFS has an amorphous or glassy appearance, with particles that look smooth and uneven in shape. The quick cooling of molten slag during processing causes their surface to be glassy or non-crystalline. Unlike FA, GGBFS generally contains angular, non-spherical particles. This is due to the fact that it is mechanically ground rather than formed from gas bubbles, as FA is. These particles can appear solid and dense, with little obvious porosity. Fractured or shattered surfaces may occur, indicating that the slag was ground into fine particles. One of the most distinguishing aspects of FA under SEM is the presence of cenospheres, which are hollow or solid spherical particles. These are formed during the burning of coal in power plants. The spheres typically have fairly smooth surfaces, though some may be pitted or porous depending on the combustion conditions. Certain particles, particularly cenospheres (hollow spheres), may exhibit interior porosity. SEM may also detect carbon-rich particles or irregularly shaped remains, particularly in lower quality FA. Particle sizes typically range from submicron to more than 100 microns. A typical SEM of GGBFS and FA are shown in figures 3 and 4.

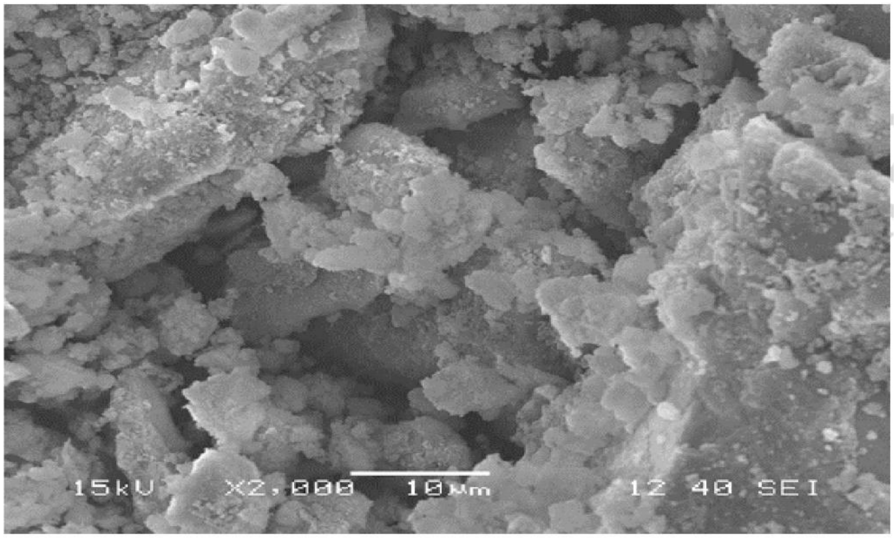

Figure 3 Scanning Electron Microscopy of GGBFS (*Ahmad* et al., *2022; Patra and Mukharjee, 2017)*

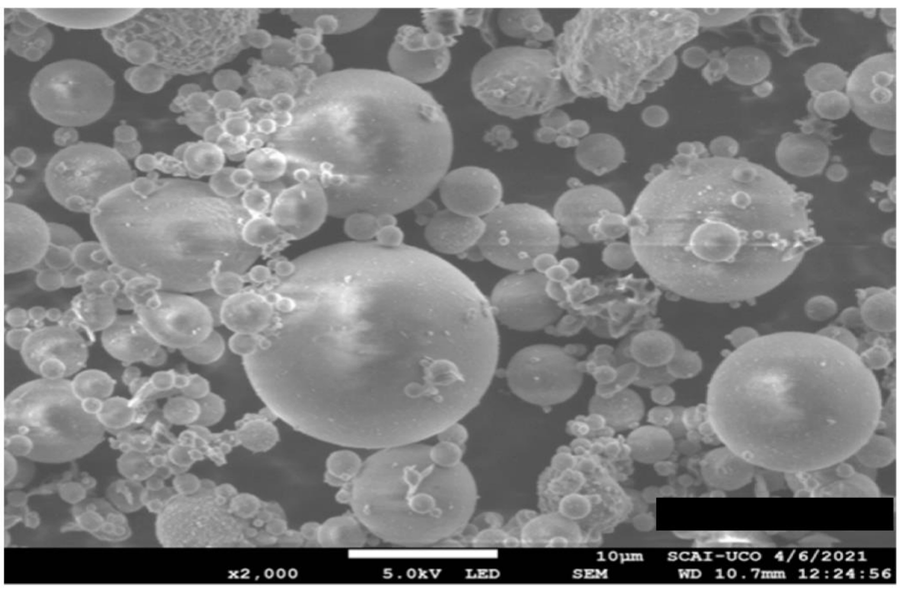

Figure 4 Scanning Electron Microscopy of FA (*Cantero* et al., *2022)*

4. CHEMICAL PROPERTIES

4.1 Pozzolanic Activity & Hydration

The chemical makeup of fly ash and blast furnace slag is vital for understanding how they behave in concrete when they are utilized as supplementary cementitious materials. The most important factor is their pozzolanic and hydraulic activity. GGBFS is latent hydraulic pozzolan, which means that it reacts with water in the presence of an activator (such as calcium hydroxide from cement) to produce cementitious compounds and then acts as a binder. While FA is a pozzolanic material that requires only water to initialize its pozzolanic activity in the existence of cement to form reaction with calcium hydroxide (obtained from cement hydration) to make more calcium silicate hydrate gel (C-S-H), it ultimately enhances the strength of the concrete. This activity depends on the specific proportions of elements like dioxide of silicon (SiO_2), aluminium oxide (Al_2O_3), and calcium oxide (CaO). Calcium oxide also helps in gaining strength by forming more hydrates. One of the most effective factors in determining the suitability of these materials to be used in cement replacement is the basicity index (the ratio of the calcium to siliceous oxide) which should be more than one. This basicity index is also controlled by the replacement of calcium oxide by magnesium oxide up to 8-10%, however, above this level it can have negative impact on the strength development (Pal, Mukherjee and Pathak, 2003). The studies concur and accept that C–S–H is the main hydration product of GGBFS and FA when cement and water are present. Due to the fact that GGBS hydrates initially much more slowly than cement, it is required to accelerate the hydration process by adding an activator, like lime, alkalis, or Portland cement. The breakage and dissolving of the vitreous slag structure brought on by the extrication of OH ions from the vitreous slag structure due to the hydration of the cement is typically what allows slag cement to be hydrated with cement. It is produced when slag cement hydrates and sodium and potassium alkalis react with calcium hydroxide to produce more C-S-H gel.

4.2 Role of Chemical Oxides

In terms of durability, resistance to chloride penetration, alkali-silica reaction (ASR), and sulphate attack are also governed by the chemical composition of GGBFS and FA. ASR is decreased and sulphate resistance is enhanced by materials that are high in alumina and low in alkalis. Oxides of magnesium, sulphur and some alkalis affect the workability and setting time of concrete. The following table shows the role of different chemical compounds in concrete. (Ahmed, Etonihu and Nweze, 2022; Lavagna and Nisticò, 2023; Lee and Lee, 2019)

Table 4 Role of chemical compounds in concrete

Chemical Compound	Formula	Role in Concrete
Silicon dioxide	SiO_2	Reacts to form C-S-H (strength & durability)
Aluminium oxide	Al_2O_3	Helps in gaining strength, sulphate resistance
Iron oxide	Fe_2O_3	Minor role, affects color
Calcium oxide	CaO	Early strength and reactivity, reduce porosity
Magnesium oxide	MgO	Reduce cracking but excess can cause expansion
Sulphur trioxide	SO_3	Helps setting, but excess can cause expansion & creep
Potassium oxide	K_2O	Rate of Hydration but interact with aggregates and causes AAR
Sodium oxide	Na_2O	Increase workability, decrease setting time, excess leads to ASR
Manganese oxide	MnO	Reduce Porosity, excess can reduce reactivity
Chloride ion	Cl	Corrosion in RCC structures

Silica, calcium, aluminium, magnesium, and oxygen make up the majority of GGBFS and FA making up over 95% of the mixture. Tables 5 and 6 lists various typical chemical compositions and the structure of GGBFS and FA used for production of concrete in previous literature.

Table 5 Chemical composition of GGBFS in previous research

AUTHORS	Chemical Compounds								
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	MnO
	GGBFS								
(Shen *et al.*, 2020)	34.62	11.82	2.73	37.37	9.43	1.42	0.35	0.5	-
(Majhi, R. K., Nayak and Mukharjee, 2018)	34	14	04	23	7	-	-	-	-
(Patra and Mukharjee, 2017)	35.6	11.74	0.8	41.7	10.7	-	-	-	-
(Gholampour and Ozbakkaloglu, 2017)	33.10	13.33	0.69	42.83	5.57	1.81	0.27	0.31	-

(Qu *et al.,* 2022)	36.93	15.55	1.86	34.69	7.21	0.66	-	-	-
(Mahmoud Elsayed *et al.,* 2022)	30.8	10.9	0.64	51.8	4.57	0.06	0.45	0.36	-
(Ramakrishnan *et al.,* 2017)	24.91	-	-	-	7.73	-	0.12	-	-
(S and Kolli, 2022)	63.15	24.83	3.1	2.63	0.66	0.13	1.43	2.79	-
(Manjunatha, Seth and Balaji, 2021)	37.73	14.42	1.11	37.43	8.71	0.39	-	0.21	-
(Shaikh, Faiz Uddin Ahmed and Hosan, 2019)	32.5	13.56	0.85	41.2	5.10	3.2	0.27	0.35	0.25
(Łukowski and Salih, 2015)	35.3	14.1	13.2	40.0	8.2	3.4	0.4	0.8	0.5
(Kathirvel and Murali, 2023)	30.97	17.41	1.03	36.77	9.01	1.82	-	-	-
(Suda and Srinivasa Rao, 2020)	37.73	14.42	1.11	37.34	8.7	-	0.39	-	-
(Gupta, 2021)	-	7.73	14.06	30.25	32.75	-	-	-	-
(Nukah *et al.,* 2022)	35.00	12.12	1.0	40	-	-	-	-	-
(Sharma and Sivapullaiah, 2016)	29.2	13.8	5.5	44.9	6.2	-	0.3	1	-

Table 6 Chemical composition of FA in previous research

AUTHORS	**Chemical Compounds**								
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	MnO
					FA				
(S and Kolli, 2022)	34.81	19.92	0.66	37.63	7.80	0.20	-	-	0.19
(Shaikh, Faiz Uddin Ahmed and Hosan, 2019)	51.11	25.56	12.48	4.3	1.45	0.24	0.77	0.7	0.15
(Nukah *et al.,* 2022)	52	23	11	5.0	-	-	-	-	-
(Mugahed Amran *et al.,* 2020)	53.8	26.72	5.2	5.7	2.3	1.5	0.6	0.7	-
(Gholampour and Ozbakkaloglu, 2017)	55.38	28.14	3.31	3.45	1.85	0.32	2.30	1.39	-
(Saha, 2018)	76.34	14.72	3.69	0.6	0.56	0.11	0.19	0.96	-
(Jena and Panda, 2018)	58.13	31	4.1	1.61	1.17	0.2	0.31	0.68	-
(Qu *et al.,* 2022)	55.91	33.18	4.88	1.93	0.95	0.51	-	-	-
(Mahmoud Elsayed *et al.,* 2022)	57.20	28.81	3.67	5.16	1.48	0.10	0.08	0.94	-
(Fan *et al.,* 2019)	62.81	21.02	11.63	4.25	1.7	-	2.23	2.06	-
(Ma *et al.,* 2017)	54.90	25.80	6.90	8.70	1.80	0.60	0.30	0.10	-
(Rotaru *et al.,* 2023)	53.17	19.03	1.33	4.05	4.71	1.92	3.76	4.96	-
(Bright Singh *et al.,* 2023)	55.4	28.2	11.1	1.17	0.67	0.42	-	-	-
(Sharma and Sivapullaiah, 2016)	54.4	28.6	3.2	1.6	1.4	-	0.3	1.7	-
(Das *et al.,* 2022)	55.31	23.68	3.95	2.35	0.83	0.28	0.35	1.97	-

4.3 XRF and Elemental Composition

The elemental composition of GGBFS and FA is determined by x-ray fluorescence method. XRF is a non-destructive analytical method for determining the elemental formation of materials. When a sample is attacked with primary X-rays, the atoms release secondary (fluorescent) X-rays that are specific to the elements present. According to EN 450-1, the combined SiO_2, Al_2O_3, and Fe_2O_3 content of FA used in concrete should be more than 70% by mass (Ohenoja *et al.,* 2019). The chemical composition of slag determines its hydraulic action. Increasing calcium, aluminium, and magnesium oxide levels leads to higher hydraulic activity, while increasing silica dioxide concentration reduces it. The mass ratio of calcium and magnesium oxide must exceed 1.0 according to TS EN 197-1 and British Standards. The reactivity of GGBFS rises with higher CaO, Na_2O, and Al_2O_3 concentrations and lower SiO_2 content. In a nutshell, the composition of GGBFS and FA plays a vital role in the hydraulic process, ultimately controlling the strength of concrete.

4.4 Phase Analysis by XRD

Phase analysis of GGBFS and FA is another way to have an idea about the identification, presence and type of crystalline minerals in these materials. X-ray diffraction (XRD) analysis is an effective method for identifying crystalline phases. Distinct chemical characteristics, reactivity and mechanical behaviors are the factors that govern the behavior of phases in different materials. The reactivity of a material (pozzolanic, hydraulic or inert) and presence of reactive or undesirable compounds can be analyzed by this method. Typically, GGBFS is predominantly amorphous (glassy), but may contain minor crystalline phases such as gehlenite ($Ca_2Al_2SiO_7$), akermanite ($Ca_2MgSi_2O_7$), and merwinite ($Ca_3Mg(SiO_4)_2$), along with traces of quartz. These crystalline phases, combined with their largely amorphous nature, contribute to its latent hydraulic activity. For FA, the crystalline phases vary between Class F and Class C types. Class F FA typically contains quartz (SiO_2), mullite ($3Al_2O_3 \cdot 2SiO_2$), and hematite (Fe_2O_3), supporting its pozzolanic activity. In contrast, Class C FA, due to its higher calcium content, may also exhibit crystalline lime (CaO) and anhydrite ($CaSO_4$) in addition to quartz, mullite, and hematite, contributing to both pozzolanic and hydraulic reactivity.". Figure 5 shows XRD result of blast furnace slag and FA compared to OPC.

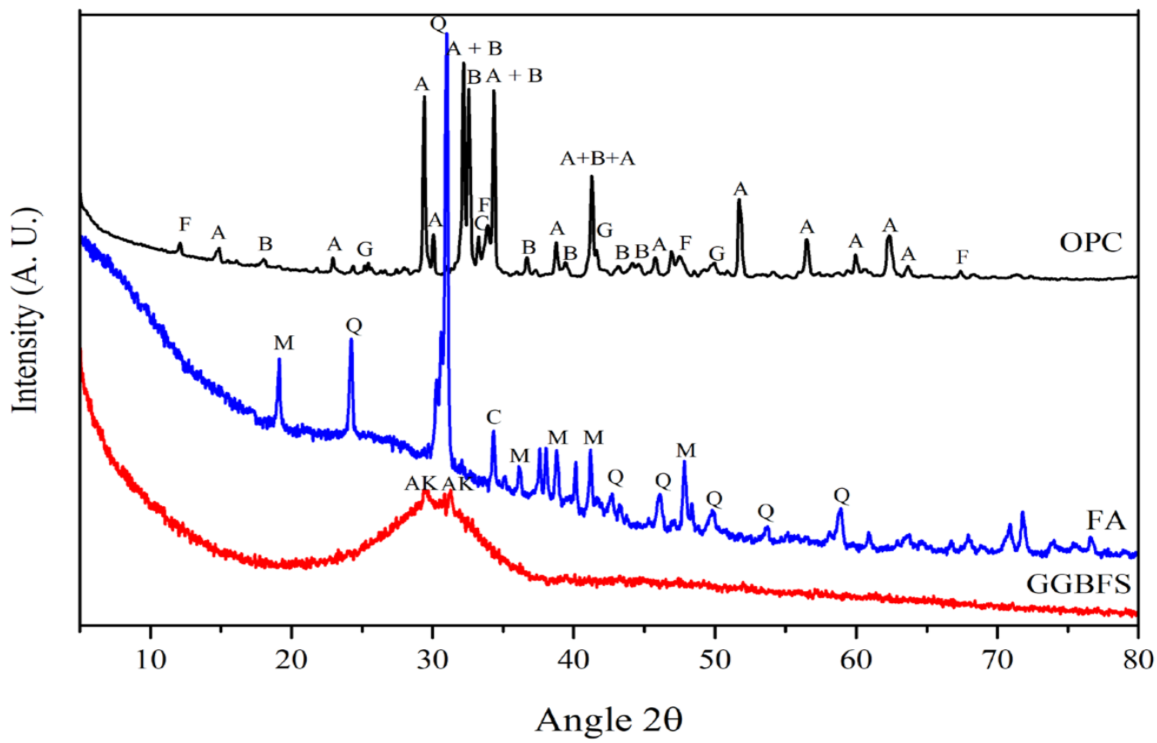

Figure 5 XRD pattern of GGBFS, Fly Ash and OPC (*Salas Montoya* et al., *2023)*

5. IMPACT ON WORKABILITY

The workability of concrete with Ground Granulated Blast Furnace Slag GGBFS and Fly Ash FA is a significant factor in mix design as they can affect concrete performance in both fresh and hardened stages. Workability describes how easy it is to mix, put (flow), compact, and finish concrete. It is often evaluated by one of the most important tests of concrete known as Slump Cone Test.

5.1 Effect of GGBFS

GGBFS has cement-like fineness but does not considerably increase water consumption. Depending on the replacement level, it may have little reduction in workability. Water absorption rate, surface area and rough texture of GGBFS are the most important factors that affect the workability of concrete (Patra and Mukharjee, 2017) Effect of steel fibers on partial replacement of cement with GGBFS in the presence of recycled aggregates was studied by (Ahmad *et al.,* 2021). The slump test showed that steel fibers and recycled aggregates had negative effect on the workability but when GGBFS was introduced in the mix, the workability was enhanced up to 20% of the replacement. This enhancement was due to the ultra-fineness of the GGBFS material. Another study conducted by Bibhu et al. (Lenka *et al.,* 2022) to form an ecofriendly concrete using slag and lime found that the workability increased with the addition of GGBFS up to a certain limit of replacement and this increase was due to the better particle dispersion of GGBFS in the mix. A researcher (Ganesh and Murthy, 2019b) also found that the workability of concrete is increased up to 40% replacement level of cement by GGBFS. Above this level, the use of admixture is advised to get the required workability. Increasing level of GGBFS requires superplasticizer to meet the requirement of workability, however FA can reduce the use of admixture and have positive impact on the workability (Dadsetan and Bai, 2017). Concrete containing GGBFS did not influence its workability, but it was easier to compact, making it more workable. At a constant water/cement ratio, increasing GGBFS had no significant impact on workability for mortar and concrete. (Hooton and R Doug , 2008; Poornima *et al.,* 2018). Research regarding concrete strength by replacing 25% of cement with slag from different sources (Parron-Rubio *et al.,* 2018) showed no effect on the slump value when the replacement level was below 30%. However, according to [65] and [66] the concrete workability increased with the addition and increased proportion of GGBFS in normal concrete and was attributed to the less absorption quality of smooth and dense particles of GGBFS.

5.2 Effect of FA

FA particles have a spherical form and behave like tiny ball bearings, enhancing flow and workability. For the same slump, they can reduce the water requirement for the mix and ultimately increase the strength. They also have tendency to reduce bleeding and segregation in pumpable concrete. The effect of use of FA on the properties and flowability of mortar was studied by (Antoni, Chandra and Hardjito, 2015). The results from the flow table test showed that the workability was increased by partial replacement of cement with FA up to 30% replacement level. Same results regarding the workability of concrete as well as mortar were obtained by (Nguyen, Saengsoy and Tangtermsirikul, 2018) by substituting the cement with FA up to 30%. At the 30% and 50% FA replacement levels of cement with FA, the slump test showed an increase in the slump height of 33.33% and 83.33% for water to binder ratio of 0.5, and for 0.4 water to binder ratio, the increase in workability was observed by 28% and 85.7% (Ikotun, Fanourakis and Mishra Bhardwaj, 2017). However, contrary to these findings, (Fantu *et al.,* 2021) found that the workability increases up to 10% replacement with FA and then decreased. This was attributed to the use of superplasticizer, however, the mix with no superplasticizer had shown increased flowability up to 20% replacement. The optimum amount of replacement of cement with GGBFS and FA was at the level of 30% replacement, above which the increase in contents of GGBFS and FA had adverse impact on the workability (Phul *et al.,* 2019). Replacing cement with FA in concrete increases workability and at the same time, reduces water consumption while maintaining the same value of slump for the same w/c ratio. Increasing FA levels can also minimize water demand, reducing the need for superplasticizer (Nayak *et al.,* 2022). The increase in the workability due to the incorporation of FA as cement replacement was attributed towards the tendency of FA to reduce the friction between the concrete ingredients including aggregates and decreasing the viscosity of the mix (Ikotun, Fanourakis and Mishra Bhardwaj, 2017). According to (Paliwal and Maru, 2017), this reduction of friction between the concrete particles was due to the spherical size of FA particles that lubricated and formed coatings around the concrete mixture.

5.3 Ternary effect of GGBFS & FA

When coupled with FA, GGBFS can improve workability properties. Azmat et al. (Phul *et al.,* 2019) performed experiments to study the effect of combining use of GGBFS and FA in concrete. The study showed that for each mix design with different proportions for cement replacement, the slump value increased. The enhanced workability was attributed to the decrease in the friction between the concrete particles because of fine and spherical particles of FA. The decreasing trend in the slump after a certain limit was attributed to the weight of the slag in the mix due to high proportions. Figure 5 shows the slump test result of concrete with partial replacement of cement with GGBFS and FA in different proportions.

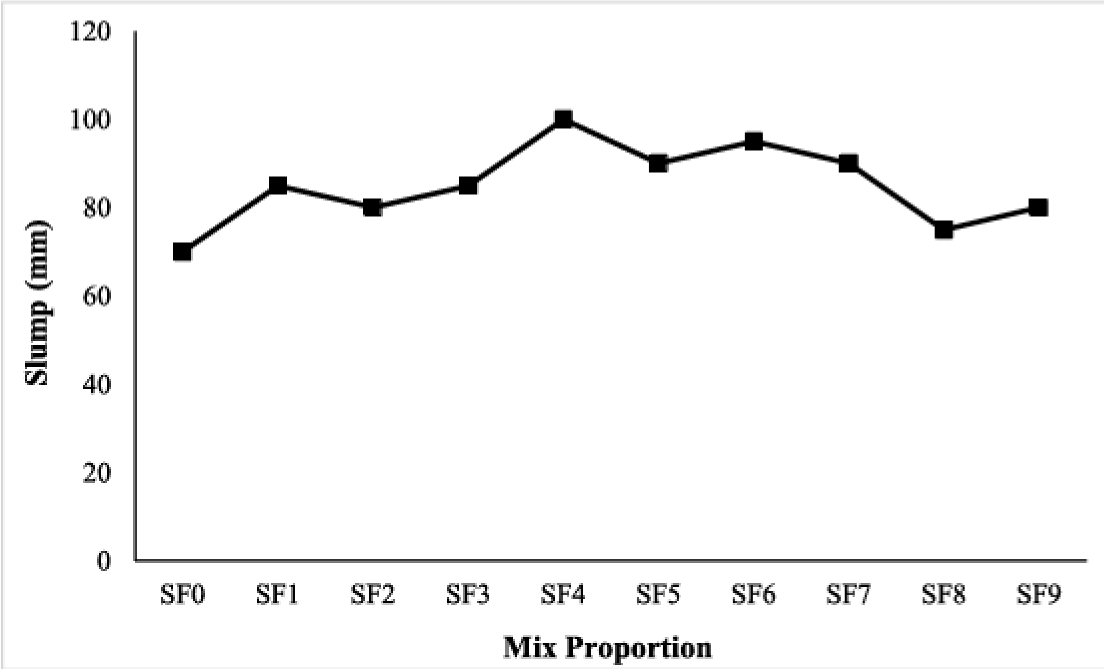

Figure 6 Slump Test Result of Concrete with GGBFS and FA (*Phul* et al., *2019)*

Mahmoud et al. studied the effect of using GGBFS and FA individually and as ternary blend in self-compacting concrete as partial replacement of cement. The slump results showed that for individual replacement levels of 25% and 50%, the workability was increased, however, more increase in the slump of the FA mixes was observed as compared to GGBFS. This result was attributed to the smooth surface and spherical form of FA particles. Similarly ternary mix with 25% GGBFS and 25% FA also showed the same trend of increased workability (Mahmoud Elsayed *et al.,* 2022). The reason for this increase was attributed to the fact the replacement was done on the basis of weight and not by volume. The capillary pore volume for this ternary mix and low specific gravity of GGBFS and FA than cement formed more quality of these materials in the mix. The same results for workability were found by Quan et al. (Quan, Tan Khoa and Tho, Mar 12, 2021) when they studied the combined effect of GGBFS and FA in sand concrete. The slump value was increased for all the samples as compared to the control mix. This increase was attributed due to the presence of FA content in a ternary mix. A higher-level replacement of cement by GGBFS and FA up to 90% were studied by (Gholampour and Ozbakkaloglu, 2017). The study comprised of 50,70 and 90% replacement of cement with GGBFS and FA individually and as ternary blends in high early strength cement. The slump results showed that all the samples with FA have more slump value than the control mixes because of the spherical shape and smooth surface of FA particles. However, a greater level of GGBFS (above 50%) lowered the workability of the concrete. This decrease was attributed to the low capillary pore volume of GGBFS mix which trapped some of the mixing water. The ternary mix has a high slump value as compared to the controlled mix with maximum workability achieved by the mix with higher volume of FA as compared to GGBFS. Contrary to this when FA concentration was made fixed at 20% and GGBFS was increased up to 60%, the results showed a gradual decrease in workability because of lower content of FA in the ternary mix as compared to the control mix (Rao, K. G., 2023). GGBFS and FA are commonly used in ternary blends. The previous research showed that FA promotes workability, but GGBFS increases durability and gains strength. GGBFS can enhance workability up to a certain level but has a neutral effect on the workability above optimum, however, it still depends on the amount of replacement, source of acquiring and mix design. Collectively, they can Improve workability than conventional cement and minimize the heat of hydration. They can also improve protection from sulphate and durability.

6. COMPRESSIVE STRENGTH

The performance, durability and strength of a concrete structure depends on the bearing capacity of the structure which is determined by the compressive strength test. (Phul *et al.,* 2019) replaced cement with GGBFS and FA at 5%, 15% and 30% replacement level. Experimental results for the compressive strength showed that the CS was increased with the increase in the replacement percentage of both materials. For M25 grade concrete, the compressive strength was increased 26.30% more than the control mix. A study conducted by (Ganesh and Murthy, 2019b) with partial replacement of cement with GGBFS found that the compressive strength increased with the increase of GGBFS content up to 20% replacement level. Above 20% replacement, the strength was decreased which was attributed to the decrease in the flowability of the concrete (Ahmad *et al.,* 2021). The increase in compressive strength with the addition of GGBFS was due to the increased pozzolanic activity of the silicon dioxide content of GGBFS that reacts with the calcium hydrate of cement (Mwiti, Karanja and Muthengia,2017). However, this pozzolanic activity was slowed at early ages and then increased gradually (Valcuende *et al.,* 2015). An experimental evaluation of geopolymer concrete incorporating GGBFS and FA showed that the compressive strength of the geopolymer concrete increased as compared to the controlled specimen with 40-60% ratios of GGBFS and FA (P. *et al.,* 2015). The following table shows the summary of compressive strength of concrete with partial replacement of cement with GGBFS and FA in previous research.

Table 7 Compressive Strength of Concrete with GGBFS and FA as per past Research

AUTHOR	**REPLACEMENT LEVEL**				**COMPRESSIVE STRENGTH (MPa)**
	CEMENT	**GGBFS**	**FA**	**TERNARY MIX [GGBFS, FA]**	
(Phul *et al.,* 2019)	100%	-	-	-	24.65
	95%,	-	-	[2%,3%], [2.5%,2.5%], [3%,2%]	25.93, 27.05, 28.12
	85%,	-	-	[5%,10%], [7.5%,7.5%], [10%,5%]	28.96, 29.14, 30.56
	70%	-	-	[10%,20%], [15%.15%], [20%,10%]	31.07, 32.22, 33.45
(Qu *et al.,* 2022)	100%	-	-	-	55.3
	80%, 70%, 60%	20%, 30%, 40%	-	-	62.1, 65.6, 61.25
	80%, 70%, 60%		20%, 30%, 40%	-	42.3, 56.1, 53.3
	65%, 60%	-	-	[15%,20%], [20%,20%]	52.26, 52.9
(Mahmoud Elsayed *et al.,* 2022)	100%	-	-	-	38.2
	75%, 50%	25%, 50%	-	-	35.4, 31.9
	75%, 50%	-	25%, 50%	-	34.1, 29.8
	50%	-	-	[25%.25%]	31
(P. *et al.,* 2015)	-	-	-	[0%,100%], [10%,90%], [20%,80%], [30%,70%], [40%,60%]	16.30, 21.11, 34.32, 42.48, 45.55, 36.84
	100%	-	-	-	64.5

(Zhao, Gong and Zhao, 2017)	30%	-	-	[20%,10%], [18%,12%], [15%, 15%]	72.1, 72.8, 74.6
	40%	-	-	[27%,13%], [24%,16%], [20%,20%]	70.2, 71.2, 71.8
	50%	-	-	[33%,17%], [30%,20%], [25%,25%]	67.8, 68.0, 70.1
(Quan, Tan Khoa and Tho, Mar 12, 2021)	100%	-	-	-	65.2
	60%	40%	-	-	66.6
	45%	-	-	[35%,20%]	62
(Punashri Prakash Phadnis, 2023)	100%	-	-	-	31.5
	70%	30%	-	-	32.1
	70%	-	-	[25%,5%], [20%,10%], [15%,15%], [10%,20%], [5%,25%]	32.6, 33.1, 37.8, 34.8, 33.6,
	70%	-	30		32.1
(Gholampour and Ozbakkaloglu, 2017)	100%	-	-	-	43.2
	50%,30%,10%	50%,70%,90%	-	-	46.2, 44.9, 40.2
	50%,30%,10%	-	50%,70%,90%	-	33.3, 22.1, 4.3
	50%,30%,10%	-	-	[25%,25%], [35%,35%], [45%,45%], [47%,23%], [23%,47%], [60%,30%], [30%,60%]	41.4, 30.9, 30.7, 42.1, 31.5, 24.5, 22.0
(Rao, K. G., 2023)	100%	-	-	-	35.39
	70%, 60% 50%, 40%	-	-	[10%,20%], [20%.20%], [30%,20%], [40%,20%]	30.46, 38.42, 33.2, 32.1
(Vollpracht, Soutsos and Kanavaris, 2018)	100%	-	-	-	31,
	70%, 50%	30%, 50%		-	25, 42
	70%, 50%		30%, 50%	-	35, 51

At different w/c ratios, the cement was replaced by GGBFS at 10, 20 and 30% replacement level were studied by (Dadsetan and Bai, 2017). The results showed that the maximum compressive strength of 81Mpa was achieved at w/c ratio of 0.4, however for all samples of replacement, the specimen with GGBFS performed well as compared to the controlled specimen. The utilization of ultra fine blast furnace slag for partial replacement of cement at w/c ratios of 0.25 and 0.35 was examined by (Teng, Lim and Sabet Divsholi, 2013a). The results showed that the ultra-fine slag has more compressive strength at w/c ratio of 0.28 which proved that fine slag requires less water to achieve the required strength. The early age strength of concrete with GGBFS is less as compared to the long-term age especially after 40 days of curing (Özbay, Erdemir and Durmuş, 2016), however, in terms of flexural strength, the incorporation of GGBFS positively affects both early and late strengths. The compressive strength of high volume GGBFS based recycled aggregate was improved with the addition of an appropriate dosage of lime (Majhi, Rajib K., Nayak and Mukharjee, 2020). This increased strength is due to the activation of GGBFS particles in the presence of lime. Another study was conducted to investigate the use of GGBFS with ionized silica to create geopolymer concrete (Vediyappan *et al.,* 2021). The compressive strength results showed that the 20% replacement had the maximum strength value when compared to 40% and 60% replacement level. The was attributed to the proportionality of hydroxide solution to molar concentration of activator in the geopolymer concrete. A ternary mix of GGBFS and micro silica was used as partial replacement of cement in a study conducted by (Suda and Srinivasa Rao, 2020). The compressive strength results showed that a mixture with 30% of GGBFS and 10% of micro silica achieved the maximum strength at 28 days. However, after 7 days, maximum compressive strength was achieved by the mix containing 20% GGBFS an 15% micro silica. These results proved that GGBFS has high strength at 28 days as compared to early strength. Contrary to this, when ultra fine GGBFS was used as a partial replacement of cement to study the effect on the workability and compressive strength along with the durability properties of concrete, the results showed that ultra fine slag caused an increase in the early strength of the concrete when used at 30% replacement of cement (Teng, Lim and Sabet Divsholi, 2013b). This was because of the large surface area of ultra fine slag which leaded to the high pozzolanic activity and ultimately enhanced the hydration process at early age of the concrete. Most of the previous research studies revealed that the particle size and chemical contents of blast furnace slag is more prominent at late strength (at 28 days) and hence have a larger surface area and fineness to have more pozzolanic activity (Jaturapitakkul *et al.,* 2019). Research conducted by Khodair et al. (Khodair and Bommareddy, 2017), included 50% replacement of cement with class C FA. The results showed that the compressive strengths at 7,14 and 28 days were 22%, 21% and 18% less than the ordinary control mix concrete. However, for the same level of replacement, compressive strength was increased by about 20% of the normal concrete mix when the cement was replaced by high volume of class F FA (Ignjatović *et al.,* 2017). However, Saha et al. found that class F FA concrete had a lower CS after 28 days of curing and a dramatic fall in strength as the FA concentration increased. In the same scenario, strength activity reactions resulted in the compressive strength of 30% and 40% FA concrete to steadily grow up and after 180 days, the results remained lower than the reference concrete for 360 days (Saha, 2018). At a water-cement ratio of 0.4, concrete with 60% FA replacement had the lowest value of compressive strength difference from conventional concrete after 7 days, compared to the experimental values obtained as that of 3 days, 28 days and late stages of strength tests at 56 days, and 90 days (Shaikh, Faiz U. A. and Supit, 2015). A combined effect of cement replacement with FA and rise husk was examined by (Jena and Panda, 2018). The study found that replacing ordinary cement with 10% FA and 20% silpozz (a type of rise husk) enhanced the compressive strength of marine concrete compared to the control sample. Another study by Xiao et al. (Wang, X. and Park, 2015), showed that 55% FA replacement level may not have higher compressive strength than control concrete at later ages due to higher water/binder ratios. However, it may have higher compressive strength if the water/binder ratio is lower. (Mugahed Amran *et al.,* 2020) studied the effect of FA replacement for cement from 10% to 50%. There was a decline in the compressive strength when the replacement level was increased beyond 10% for all ages of concrete. The researchers found out that the compressive strength of both normal and FA concrete increased with time, and this was attributed to OPC hydration and FA's higher pozzolanic reactivity with time. A compressive strength study of using FA and slag as partial replacement of cement was performed at different ratios of 5%, 10% and 15% (Xu *et al.,* 2017). The results showed that all the samples had more compressive strength after 28 days but at 7 days strength of the control specimen was more than the test specimens. However, at 14 days, the strength of FA specimen is more than the control one but less than the concrete with slag. A 10% increase in the compressive strength of concrete having 125kg/m^3 FA as partial replacement of cement, but for the same mix, the compressive strength was decreased u to 17% when the FA was increased from 125kg/m^3 to 150kg/m^3 (Iqbal *et al.,* 2017). In another study researchers examined how FA affected concrete with combination of silica fume and discovered that as FA concentration increases, the 28-day compressive decreased, however, the compressive strength of concrete with 10% FA was the same as that of the control mix (Sadrmomtazi, Tahmouresi and Kohani Khoshkbijari, 2018). However, the addition of silica fumes increased the 90 days compressive strength of the said mix compared to the control one. The effect of using GGBFS and FA in conventional concrete individually and as ternary blend on compressive strength is described in table:

Table 8 Effect of GGBFS & FA on concrete strength

COMPRESSIVE STRENGHT OF CONCRETE			
AGE	**GGBFS only**	**FA only**	**GGBFS+FA**
3 days	Low	Low	Low-Moderate
7 days	Low-Moderate	Low-Moderate	Moderate
14 days	Moderate	Moderate	Moderate
28 days	High	High	Higher
56-90 days	Higher	Higher	Highest

7. TENSILE STRENGTH

Particularly with appropriate curing, concrete containing GGBFS and FA exhibits reduced tensile strength at early ages but equivalent or marginally superior tensile strength at late stages. Replacement levels, curing conditions and time, w/c ratio and aggregate properties are some of the factors that affect the tensile strength of concrete with GGBFS and FA. The split tensile strength of a geopolymer concrete with GGBFS and FA showed that the optimum percentage of GGBFS and FA is 40% and 60% respectively to have maximum tensile strength at 28 days i.e. 5.94N/mm^2 (P. *et al.,* 2015). Ramani et al. investigated the use of GGBFS and black rice husk ash in geopolymer concrete with 10, 20 and 30% replacement of GGBFS with rice husk ash (Prasanna Venkatesan Ramani and Pazhani Kandukalpatti Chinnaraj, 2015). The split tensile strength of the sample with 10% replacement of GGBFS with rice husk ash was maximum and then it was decreased with the increase in the content of ash. This was attributed to the more fineness of rice husk ash and with the increase in the ratio of alkaline solution i.e. SiO_2/Al_2O_3. An experimental analysis on optimum usage of silica and GGBFS for partial replacement of cement in concrete showed that for w/b ratio of 0.55, there was a 15.29% increase in the split tensile compared to the conventional concrete (Suda and Srinivasa Rao, 2020). The results also showed that the mix with 30% GGBFS and 10% micro silica showed better performance in terms of split tensile strength. An optimum amount of 40% replacement of blast furnace slag with biomass silica was recommended by Vediyappan et al. (Vediyappan *et al.,* 2021). The results showed the split tensile strength of the sample was increased when the replacement level was 40% and then decreased and a maximum split strength of 4.621Mpa was observed as result of experiments. This increase in the mechanical properties of concrete was attributed to the presence of secondary calcium silicate hydrate solution in the mixes containing biomass silica. Kumar et al. found that adding 10% LS (lime sludge) and 8% SF (silica fume) with 15% FA increased the split tensile strength in concrete with mix design of 30 by 19.54%. For concrete with design strength of 50 and 70 Mpa, the same mix of replacement increased the strength by 12.46 and 13.35%, respectively. The study found that the rate of reaction was significantly influenced by the size and surface area of the particles. Higher strength was the outcome of the extra CSH gel that developed when lime sludge was introduced into the mix (Praveen Kumar and Ravi Prasad, 2019). At early ages of up to 28 days, FA with low calcium content concrete demonstrated lower flexural tensile strength and split tensile strength than plain concrete, but, at later ages, when it was tested at 28days and more, it was like plain concrete, according to Hashmi et al. (Hashmi, Shariq and Baqi, 2021). The research showed that the 40% replacement of cement with FA can be considered as optimum percentage with maximum performance in terms of mechanical properties of concrete. A combined effect of glass fibers and FA in cement concrete was examined by (Barbuta *et al.,* 2017). The FA was used as partial replacement of cement by 10,15,20,30 and 40% by weight. The fibers dosage was kept constant at 0.25%, however, fibers with two lengths i.e. 30mm and 50mm were incorporated into the mix. The results showed the tensile strength was increased with the addition of glass fibers of 50mm length and the optimum amount of silica fume used was 10% for tensile strength. The split tensile strength if the samples was highly influenced by the dosage and length of the fibers introduced into the mix. The induction of fibers also enhanced the durability characteristics of concrete with FA.

The split tensile strength of concrete containing ternary mix of GGBFS and FA as 35% and 45% with (15%,20%) and (20%,20%) level of GGBFS and FA studied by (Qu *et al.,* 2022) showed a lower tensile strength at early ages but marginally close values to the control mix at the age 28 days for 35% replacement level. The reason for the decrease is the reduced hydration process because there is a large amount of water required for activation of this hydration process. Mehmood et al. (Mahmoud Elsayed *et al.,* 2022) observed the same results for split tensile strength that was decreased with ternary mix of GGBFS and FA. The main reason for the reduction in the strength was attributed to the low CaO content and higher SiO_2 contents in GGBFS and FA. It was also observed that FA had more critical reasons for the reduction in split tensile strength. A partial replacement of cement in sand concrete with GGBFS and FA was studied by (Quan, Tan Khoa and Tho, Mar 12, 2021) with 35% of GGBFS and 20% of FA as ternary mix with cement. The results of split tensile strength showed that the ternary sample had lower early strength even at 28-days but at 56 days the tensile strength was increased compared to the control mix. The initial decrease in strength was due to reduced hydration process because of lower CaO content in GGBFS and FA. However, at later stages, the presence of SiO_2 content in GGBFS and pozzolanic activity of FA that consumed the Ca $(OH)_2$ to form more C-S-H gel and made the concrete harder. A higher level of replacement i.e. 50%, 70% and 90% of cement with different ratios of GGBFS and FA using high early strength cement were examined by (Gholampour and Ozbakkaloglu, 2017). The split tensile strength results showed a decrease at 28days but at 56 days the strength of most of the samples was marginally close to the control mix at 50% level of replacement of GGBFS and FA when used with ratio 1:1. This late increase in the strength of concrete was attributed to the high level of SiO_2 and Al_2O_3 in GGBFS and the late pozzolanic activity ability of FA which lets OH and Ca $(OH)_2$ group in the concrete mix to interact with high contents of C_3S, C_2S and C_3A in high strength cement, enhancing the hydration products of calcium-silicate-hydrate gel.

The early age strength of concrete with GGBFS and FA is lower than the control mix, however it improves with the time at have maximum value at 56-128 days of curing. This is because of the ongoing pozzolanic and latent hydraulic reactions in case of GGBFS and particle fineness in case of FA. However, their combination in concrete can synergistically enhance durability and long-term strength if properly proportioned.

8. FLEXURAL STRNGTH

To assess the bending ability and insight behavior of the material, determination of flexural strength is important. A low flexural strength concrete can lead to early cracking, causes steel to corrode, and eventually results in structural failure. Flexure strength plays a pivotal role in the design of rigid pavements and pre-cast concrete structures. It aids the designers in determining whether fiber additions or reinforcement are required for the concrete or not. Generally, the early flexural strength of concrete with GGBFS and FA is low as compared to normal concrete and eventually increases at late ages. Vignesh et al. Studied and investigated the effect of GGBFS and FA in geopolymer concrete at 90/10, 80/20, 70/30, 60/40 replacement level of FA/GGBFS. The flexure strength results showed that the maximum strength was obtained at 60/40% level, and only the specimen with 70/30% and 60/40% had more strength than the conventional control mix (P. *et al.,* 2015). A two-point loading test was performed to examine the flexural strength of the concrete with GGBFS and micro silica. The results showed that the flexure strength was enhanced by 17% up to the overall replacement level of 40% of cement (Suda and Srinivasa Rao, 2020). The same trend was followed when the strength was measured at 90, 180 and 365 days respectively. A geopolymer concrete with GGBFS replaced with 10, 20, 30, 40 and 50% of biomass silica was analyzed by (Vediyappan *et al.,* 2021). Flexure strength experiments revealed 40% replacement of GGBFS by silica as the optimum level that showed the better performance as compared to other mixes. Another study was conducted with replacement of GGBFS by rice husk ash with different percentages showed that the flexural strength was increased up to 10% replacement of GGBFS with FA and then decreased on further replacement. Maximum flexural strength at 28days strength was 6.98 Mpa as compared to 6.06 Mpa of the control mix at 28 days (Prasanna Venkatesan Ramani and Pazhani Kandukalpatti Chinnaraj, 2015). A study regarding the replacement of cement with FA, silica fumes and lime sludge for three different concrete mix designs i.e. 30,50 and 70Mpa was investigated (Praveen Kumar and Ravi Prasad, 2019). The results regarding the flexural strength of all the test specimens showed that the FS increased when the optimum percentage 15% FA, 8% SF and 10% LS of supplementary cementitious materials was incorporated as partial replacement of cement. When FA concrete without fibers was used, a 10% FA substitution yielded the maximum value compared to the control design mix. (Barbuta *et al.,* 2017). However, for the same mix, when fibers were introduced in the mix with 0.25% of dosage, there was an increase in the flexural strength for the concrete having 20% replacement of cement with FA. The results showed that the FS was also increased for the specimen having 30 and 40% replacement of cement with FA but the maximum value of 2.16Mpa was obtained at 20% level. For lower replacement of cement, use of fibers was recommended to enhance the flexural strength characteristics of such concrete mixes.

The study conducted by (Qu *et al.,* 2022) showed that the flexural strength of all the samples with ternary mixes decreased at early ages and the same pattern was observed at late ages as well. The decrease in strength gradually increased at late ages because of the reduction in the calcium concentration between cement/binders and aggregates. A partial replacement of cement in sand concrete with GGBFS and FA was studied by (Quan, Tan Khoa and Tho, Mar 12, 2021) with 35% of GGBFS and 20% of FA as ternary mix with cement. The results of flexural strength showed that the ternary sample had lower early strength even at 28 days but at 56 days the flexural strength was increased compared to the control mix. The initial decrease in strength was due to reduced hydration process because of lower CaO content in GGBFS and FA. However, at later stages, the presence of SiO_2 content in GGBFS and pozzolanic activity of FA that consumed the Ca $(OH)_2$ to form more C-S-H gel and made the concrete harder. A reduction in 9% flexural strength was observed compared to the control mix when 25% GGBFS and 25% FA were used as partial replacement of cement in self-compacting concrete. The main reason was the poor internal structure of concrete due to the weak bond between the binders and the aggregates. Gholampour et al. (Gholampour and Ozbakkaloglu, 2017) found that the flexural strength can be enhanced as compared to the control by using ternary mix of GGBFS and FA in the presence of high early strength cement at 56 days age. However, this increase was limited to marginal equivalency to the control mix at 50% replacement level. The higher content of SiO_2 and Al_2O_3 in GGBFS and late pozzolanic activity of FA were attributed as the main reasons for this enhancement in strength at 56-days as compared to the strength at 7, 14 and 28 days.

The literature showed that the combination of GGBFS and FA can be used to enhance the flexural strength, and it can exceed the control strength. If these SCMs are introduced individually then GGBFS will have the same flexural strength as that of control at 28-56 days but for FA concrete the FS will be slightly lower at 28 days but improves with time.

9. ADVANTAGE OF HIGH LATE STRENGTH WITH TERNARY USE OF GGBFS & FA

Most of the literature showed gradual enhancement in the mechanical properties of concrete made with partial replacement of cement with GGBFS and FA at higher ages i.e. 28 days, 56 days and 90 days. Getting more late-age strength compared to early-age strength when using GGBFS and FA as partial cement replacements has several significant advantages, especially for certain types of concrete applications and is sometimes sufficient to offset early strength losses. Sustainability is ensured by using byproducts and waste like GGBFS and FA as they are cheaper as compared to cement and can reduce the concrete cost. This also helps to improve environmental footprints by securing low CO_2 emissions. One of the most important advantages is the improved durability and long-term performance of concrete ensured by the denser microstructure. The continued pozzolanic and latent hydraulic reactions of GGBFS and FA reduce the permeability and improve the resistance against chloride penetration, sulfate attack, AAR (alkali-aggregate reaction), ASR (alkali-silica reaction) and carbonation. Slower strength gain of GGBFS and FA reduce the heat of hydration and helps in minimizing thermal gradients and associated cracking risks. However, when there are situations where early strength is important and required, these SCMs can be combined with admixtures like accelerators or high early strength superplasticizers and early strength cement (Gholampour and Ozbakkaloglu, 2017). In some cases, enhancements in curing techniques temperatures such as steam curing can be helpful in increasing the early mechanical strength of concrete.

10. ENVIRONMENTAL IMPACT

Efforts are being made to produce concrete using alternative binder ingredients instead of ordinary Portland cement due to growing environmental sustainability concerns in the building sector and a need for more sustainable concrete. Environmental impacts of concrete made with different pozzolanic materials as partial replacement of cement were analyzed by (Hossain *et al.,* 2021). The study involved the use of GGBFS, FA and volcanic ash as SCMs. SimaPro 9.1.5 software was used to simulate all of the materials, their transportation, and their operations for the concrete production process investigated. The results indicate that with the defined system boundaries, all the SCMs have less impact on the environment as compared to the ordinary concrete with OPC. A life cycle assessment on the use of recycled aggregates with silica fume and GGBFS as partial replacement of cement was performed by (Shamass *et al.,* 2023) using SimaPro, version 9.1.1. The boundary conditions and considerations were set with a focus on Global Warming Potential (GWP). The results indicated that using GGBS and silica fumes in place of cement in a concrete mixture with normal and recycled aggregates has a major GWP impact in terms of CO_2 emissions in the environment. The CO_2 emission per unit volume of cement production is 771.7 kg/ton as compared to the production of GGBFS and FA which are 40.36 kg/ton and 23.0 kg/ton respectively (Liu, Z. *et al.,* 2022). The study involved the use of GGBFS and FA as cement replacement and the mechanical properties with the focus on creep and shrinkage. They used the recommendations provided by the Environmental Performance Verification for Concrete Structures (EPVCS) to calculate the carbon emission with each concrete mix they made. Concrete with GGBS in place of sand showed reduced CO_2 emissions in terms of the ratio of CO_2 emissions to compressive strength, while concrete with 30% GGBS in place of sand showed around half the CO_2 emissions in comparison to the control concrete. The manufacturing of cement results in significant CO_2 emissions per unit volume; however, it has been demonstrated that the environmental impact can be mitigated by substituting fly ash or GGBS for cement (Flower and Sanjayan, 2007). A comparative study was conducted to assess the environmental impact of FA from two different sources i.e. Biomass FA and Coal FA (Teixeira *et al.,* 2016). The embodied environmental impacts (cradle-to-gate) of the various concrete compositions and the environmental effects resulting from the materials' transportation and mixing at the concrete factory were delineated by the boundaries of this work. The findings demonstrated that the Portland cement content of concrete is primarily responsible for the potential environmental impact of concrete, particularly the portion associated with CO_2 emissions. When compared to conventional concrete, the use of coal and biomass fly ashes demonstrated the ability to lessen the environmental impacts of concrete. According to the findings, concrete that uses 60% biomass fly ashes in place of cement is the best. The findings also demonstrate that concretes with a lower Portland cement percentage might nonetheless have better environmental outcomes. Life cycle assessment of CO_2 emission in mortar with partial replacement of cement with GGBFS and FA as blended Cement Systems. The study investigates the depth of carbonation in cementitious materials and additives, showing that FA increases depth because of delayed reactions, while GGBS decreases depth (Liu, J. *et al.,* 2024). By reducing carbonation depth through densification, GGBFS blended cement highlights the effects of materials and additives, whereas higher FA concentration increases depth through delayed reactions and increased porosity. Because of their higher porosity, FA blends have more carbonation, while GGBS blends have less depth because of their refined pore structures from secondary reactions. A typical example of embodied carbon emission by cement , GGBFS and FA is shown in figure 7.

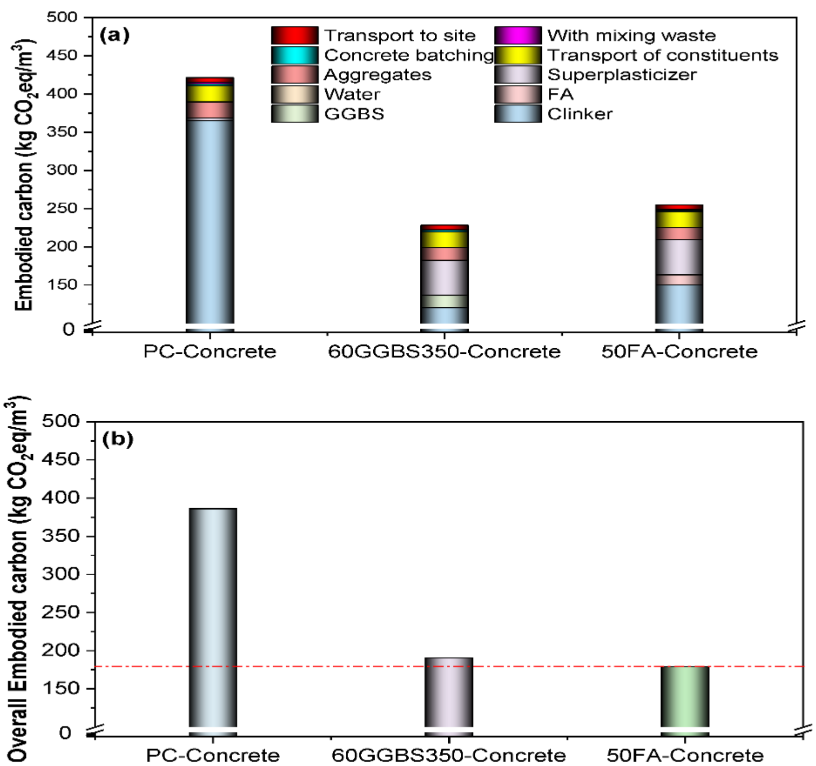

Figure 7 Embodied carbon emissions by each component (a) without considering carbon capture; (b) with the consideration of carbon capture (Liu, J. et al., *2024)*

The use of GGBFS and FA as partial cement replacements can significantly reduces the environmental impacts of concrete and promotes sustainable construction practices. They require significantly less energy and lower emissions for processing and can reduce CO_2 emissions by up to 30–60%, depending on replacement levels. These materials also require minimal additional processing like grinding.

11. RESEARCH POTENTIAL FOR SUSTAINABLE CONSTRUCTION

The use of supplementary cementitious elements in concrete is a popular area of study these days, and it is becoming increasingly crucial in achieving sustainable development goals in the building industry. They can be a significant enhancement in terms of sustainability by ensuring the use of industrial waste, reduction in carbon footprints, durability enhancement and encouraging the circular economy. The incorporation of supplementary cementitious materials (SCMs) such as Ground Granulated Blast Furnace Slag (GGBFS) and fly ash (FA) into concrete has emerged as a pivotal strategy in promoting sustainable construction. These materials, primarily industrial by-products, offer substantial environmental benefits by reducing the reliance on Portland cement—a material known for its high carbon emissions and energy consumption. Their effective utilization aligns directly with the United Nations Sustainable Development Goals by fostering circular economy practices, minimizing industrial waste, and improving long-term durability of concrete structures.

Despite the extensive research into the individual properties of GGBFS and FA, several knowledge gaps remain that warrant further investigation to maximize their sustainable potential in real-world applications.

10.1 Synergistic Use of SCMs

A key area for future research lies in the development of synergistic and hybrid combinations of SCMs. Although the individual performance of GGBFS and FA has been documented, the combined effects on hydration, strength development, and setting behaviors are not fully understood. Research is needed to explore optimal replacement ratios and the interaction between various SCMs under different curing regimes, particularly in mixtures designed for high-performance or ultra-high-performance concrete applications.

10.2 Durability in Aggressive Environments

The long-term durability of SCM-based concretes in aggressive environments such as those prone to alkali-silica reaction (ASR) and alkali-aggregate reaction (AAR) is another critical topic. While some studies suggest that GGBFS may mitigate ASR due to its low alkali content, the effectiveness of different SCM blends under severe environmental exposure remains inconclusive. Future work should include experimental and field-based evaluations to understand resistance mechanisms and establish guidelines for durability design.

10.3 Advanced Predictive Modelling

The use of artificial intelligence and machine learning (ML) techniques represents a promising approach to optimize concrete mix design and predict material performance. Supervised learning models, such as artificial neural networks or decision tree regressors, can be trained using experimental datasets to predict key mechanical and durability parameters based on SCM type, particle size, dosage, and curing time. Research should focus on developing reliable, generalizable models and integrating them into design tools for practical use by engineers and contractors.

10.4 Life Cycle Assessment (LCA) and Environmental Impact

Comprehensive life cycle assessments of SCM-based concretes are essential to quantify their true environmental benefits. This includes evaluating embodied carbon, energy consumption, and waste reduction over the entire lifecycle—from raw material processing to end-of-life. Comparative LCAs between SCM concretes and traditional mixes can help determine under which conditions the use of GGBFS and FA offers net sustainability gains.

10.5 Alkali Activation and Reactivity Enhancement

Emerging research on alkali-activated binders highlights the potential for GGBFS to be combined with other pozzolanic materials, such as metakaolin or rice husk ash, to produce high-strength, cement-free concrete. However, the underlying chemical mechanisms, such as the formation of calcium-alumina-silicate-hydrate (C-A-S-H) gels, remain insufficiently characterized. Future studies should examine the influence of activator type, solution molarity, and curing temperature on the reactivity and mechanical performance of such binders.

10.6 Standardization and Policy Integration

Finally, the translation of laboratory findings into industry practice depends on the development of clear testing protocols and updates to construction standards and codes. Current standards in many countries either restrict or inadequately address the use of high-volume SCMs. Research is needed to assess performance-based criteria for SCM concrete and support the formulation of prescriptive codes, especially for public infrastructure projects where safety and reliability are paramount and to evaluate the compatibility of SCM-based concrete with existing design codes and to develop guidelines for standardized adoption in public infrastructure.

12. CONCLUSIONS

This review explores the effectiveness and use of GGBFS and FA to enhance concrete properties. Their production processes, physical properties, chemical content and characteristics, and the impact of their use on its fresh properties and hardened mechanical strength characteristics were discussed. The purpose of this paper was to raise awareness about the use of GGBFS and FA in relation to potential environmental effects and technical benefits for sustainable building in the construction field. The general observations and calculations from previous research can be summarized as follows:

- GGBFS has latent hydraulic properties, meaning it requires activation (e.g., by calcium hydroxide from cement hydration) to contribute to strength whereas FA is pozzolanic, reacting with calcium hydroxide to form additional gel in the form of C-S-H (Calcium Silicate Hydrate), enhancing strength and durability. Together, they result in a more efficient and extended pozzolanic reaction, which can improve later-age strength more significantly than alone and optimize both early strength gain (due to GGBFS) and long-term mechanical strength (due to FA)

- The general effect of combined use of GGBFS and FA on the workability of concrete is generally positive because of improved rheology by the round FA particles improve flow, while GGBFS refines the particle packing, reducing internal friction and segregation ultimately enhancing the workability of concrete. Spherical particle shape of FA acts like tiny ball bearings, lowering the water demand, improving flowability, enhances cohesion and reduces bleeding. For GGBFS, angular but smooth particles, finer than cement tend to slightly increase water demand, but not as much as OPC and when used with FA, have positive impact on the workability of concrete.

- The early-age compressive strength (1–7 days) tends to be lower compared to conventional OPC concrete, especially with high FA content. GGBFS can mitigate this drop slightly due to its latent hydraulic nature. The combination still has a low effect on the hydration process early on, so early compressive strength may be reduced. However, for later-Age Strength (28 days and beyond), significant improvement in compressive strength is examined compared to control mix with OPC alone. FA reacts slowly but produces additional C–S–H by consuming $Ca(OH)_2$. GGBFS contributes both through its own hydration and by promoting the hydraulic reaction ultimately increasing the pozzolanic activity of FA. The continued formation of C–S–H as the result of this reaction densifies the matrix, improving strength.

- The early age tensile strength may be lower compared to conventional Portland cement concrete due to slower hydration. However, long term tensile strength improves prominently over time because of the ongoing pozzolanic and latent hydraulic reactions. A typical increase of around 10–20% improvement after 90 days compared to control OPC mix is expected depending on mix design.

- Flexural strength is often lower than that of conventional Portland cement concrete when tested at an early age. This is because both GGBFS and FA react more slowly than OPC. However, for later ages, the FS tends to improve significantly, often matching or exceeding that of control concrete, especially when cured well (moist curing is critical for SCM-blended concretes). The combination of GGBFS and FA can result in better long-term flexural strength due to improved microstructure and pozzolanic reactions.

- The use of GGBFS and FA as partial cement replacements can significantly reduce the environmental impacts of concrete and promotes sustainable construction practices. They require significantly less energy and lower emissions for processing and can reduce CO_2 emissions by up to 30–60%, depending on replacement levels.

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