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REVIEW

A review on various aspects of high performance concrete

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Abstract
The requirement for high-performance concrete has increased day by day due to its better performance. Due to its strength, durability, and high modulus of elasticity, high-performance concrete has predominantly been employed in constructing large-scale civil engineering structures, e.g., tunnels, bridges, pavements, and high-rise buildings. The various characteristics of HPC, like workability, strength, modulus of elasticity, durability in terms of permeability of fluids through concrete, sorptivity, and resistance to chemical attack, have been reviewed in this study. The properties above are generally assessed while constructing any concrete structure. It is well known that a million numbers of pores are available in concrete structures. The interconnected pores affect the durability of the concrete, which can be reduced by using the SCMs. The most used SCMs, i.e., ground granulated blast furnace slag, fly ash, and silica fume, in HPC, are the by-product of waste materials obtained from industries and are harmful to the environment. Stringent environmental norms help reduce the varying degrees of environmental impacts of throwing away such waste products. The present study highlights the utilization of mineral and chemical admixtures, as the admixtures are used to enhance the chemical, physical and mechanical properties of concrete. The present study suggests reusing these waste materials to improve the performance of concrete, which impacts society.

Keywords High-performance concrete · Compressive strength · Modulus of elasticity · Permeability · Sorptivity

Abbreviations

ACI	American concrete institute
CNI	Calcium nitrite inhibitor
CSH	Calcium silicate hydrates
DAC	Dry air curing
EN	European standards
FA	Fly ash
FBG	Fiber Bragg grating
GA	Genetic algorithm
GFFN	Generalized feed-forward neural network
GFRHPC	Glass fiber reinforced high-performance concrete
GGBS	Ground granulated blast furnace slag
GGFAC	Ground granulated blast furnace slag fly ash
HFAC	High volume fly ash concrete
HPC	High performance concrete
IS	Indian standards
LCA	Life cycle assessment
LWS	Lightweight sand
MIP	Mercury intrusion porosimetry
NPC	Normal Portland cement concrete
NSC	Normal strength concrete
PCC	Portland cement concrete
PFA	Pulverized fly ash
RHA	Rice husk ash
SCC	Self-compacting concrete
SCM	Supplementary cementitious materials
SF	Silica fume
SHRP	Strategic highway research programme
WC	Water curing
WRC	Wrapped curing

Introduction

Background

High-performance concrete (HPC) is a type of concrete with improved mechanical and durability characteristics compared to normal concrete. HPC was developed in the late twentieth century in response to the need for stronger and more stable concrete structures. Rosenberg

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and Gaidis [1] examined that the HPC is made using specialized materials and techniques, including the use of superplasticizers, high-range water reducers, and pozzolanic or mineral additives. These materials enhance the strength, workability, and durability of the concrete. Over the last few decades, HPC has been utilized at a higher level as a construction material worldwide. Nowadays, the construction industry is growing rapidly because many countries use natural resources for infrastructure development. HPC is engineered concrete made of cement, fine aggregate, coarse aggregate, water, and admixtures. Neville and Aitcin [2] discussed that HPC is not technically different from the standard concrete used in the past, but it uses industrial wastes to fulfill specific construction needs. Aitcin et al. [3] mainly discussed the shrinkage behavior of HPC and curing conditions. HPC has high workability, high modulus of elasticity, high strength, high durability, low permeability, high resistance to chemical attack, high dimensional stability, and high density [4, 5]. HPC is additionally referred to as durable concrete due to its impregnability to chloride penetration, and its high strength makes it useful for longer than normal concrete. Sufficient moisture content is necessary during the early age of concrete. One may use the single-point magnetic resonance imaging method to determine the effects of moist curing and the utilization of curing compounds on the mass and distribution of moisture during the drying of high-performance and ordinary concrete [6–10].

From an economic point of view, the long-term performance of concrete structures becomes significant to us. Concrete is a massive tool for manufacturing reliable and stable infrastructure. As a replacement material for the ingredients used in concrete manufacturing, the use of waste products is also growing day by day. The popularity and importance of high-performance concrete are increasing continuously because of its superior durability and mechanical properties. One of the foremost important properties within HPC manufacturing is the exclusion of voids within the concrete matrix, which is the primary reason behind concrete deterioration. Muller and Haist [11] discussed the new types of HPC, like ultra-high strength concrete and self-compacting concrete (SCC). The study addresses the stabilizer & powder type SCC, variations in the composition & mix design of concrete, and hardened & fresh state properties. Ultra-high strength concrete is found to be much more sustainable than conventional concrete.

Conventional concrete mix, which mainly depends on compressive strength, may not fulfill numerous working needs because there has been a shortage in energy absorption capacity, repair, retrofitting tasks, aggressive environment, and construction time [12–14]. So, it is necessary to produce high-performance concrete that is much better than normal concrete because HPC constituents contribute superiority to the various properties. Several current construction practices use waste materials, including:

i. Recycled aggregate concrete: using recycled materials such as crushed concrete, bricks, and asphalt as a substitute for natural aggregates in concrete.
ii. Waste-based bricks: using waste materials such as fly ash, slag, and construction waste to produce bricks for building construction.
iii. Plastic waste as a construction material: using recycled plastic waste to produce items such as decking, fencing, and roof tiles.
iv. Waste wood in construction: using waste wood, such as pallets, crates, and demolition wood, to produce engineered wood products, such as flooring, sheathing, and structural beams.
v. Tyre recycling: using waste tyres as an alternative to traditional construction materials, such as sand and gravel, to produce items like road foundations, floor tiles, and interlocking blocks.

These construction practices help reduce waste and conserve natural resources while promoting sustainable construction. Nowadays, structures are mostly constructed with concrete as the raw materials are easily available nearby, and their molding can be done quickly with the help of unskilled labor.

Overview of study

The significant literature available on HPC has been published in the last two decades only, and a few are available from the early 1990s. Figure 1 reveals the major publications

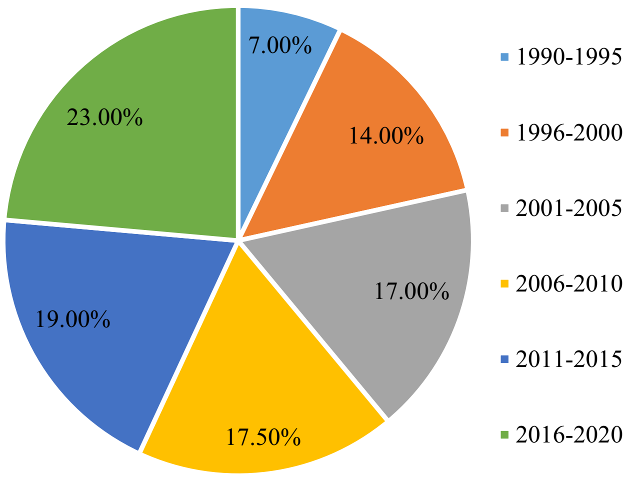


Fig. 1 Major publications appeared in every 5-year period expressed in percent of total publication since 1990s

in terms of the percent of total publications on HPC since the 1990s. The figure reveals that only around 7.5% of the total publications appeared up to 1995, and then the major publications subsequently increased steadily, and about 23% of the total publications were published during 2016–2020. The study area of HPC is a new promising area in the construction industry, and the number of publications is gradually increasing. A substantial amount of literature has been published in the last 1.5 decades, reviewed in this paper. A flowchart, shown in Fig. 2, depicts the classification of headers and sub-headers of the present study. The present study reviews the various properties of HPC in the cementitious matrix using SCMs.

Methods for achieving high performance

There are several applied methods for producing high-performance concrete (HPC). Some of the most common methods include:

i. Use of high-strength and high-performance cement: The use of specialized cement with high early strength and low permeability can significantly improve the properties of HPC.
ii. Use of supplementary cementitious materials (SCMs): SCMs, such as fly ash, slag, and silica fume, can improve the workability, strength, and durability of HPC while reducing the amount of cement required.
iii. Use of chemical admixtures: Chemical admixtures, such as water reducers, air-entraining agents, and superplasticizers, can improve the workability, strength, and durability of HPC while reducing the amount of water needed.
iv. Proper mix design: An optimized mix design can ensure that the HPC has the desired properties, such as high strength and low permeability.
v. Quality control measures: Implementing quality control measures throughout the production process can ensure that the HPC is consistently produced to the desired specifications and that the desired properties are achieved. Quality control of high-performance concrete involves careful selection and testing of materials, optimization of mix design, process control during production, testing, performance evaluation, documentation and record keeping, and training and certification of personnel. Testing and evaluating the quality of raw materials such as cement, aggregates, admixtures, and water used in producing HPC. Developing and optimizing the mix design of HPC may involve conducting trial mixes, testing the properties of fresh and hardened concrete, and adjusting the mix proportions to ensure that the concrete meets the required performance criteria. Conducting tests

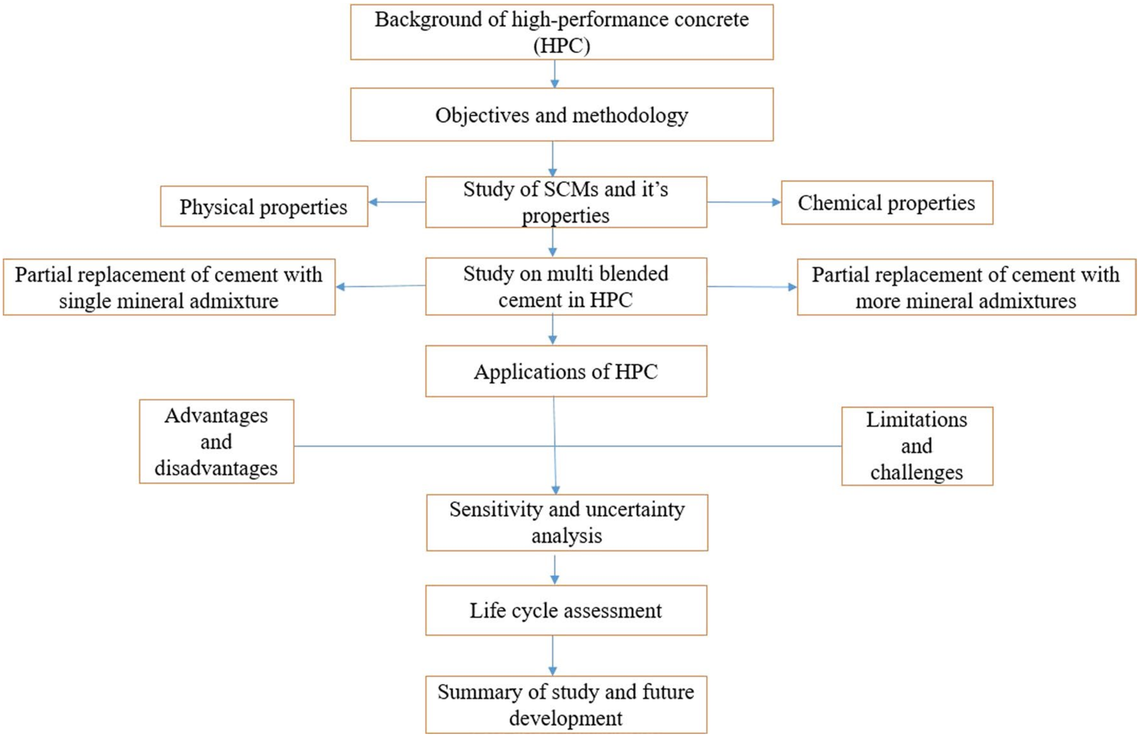


Fig. 2 Flowchart for systematic review of publications

on freshly mixed HPC, such as slump, air content, temperature, and workability, to ensure that the concrete is within the specified limits and is suitable for placement. Monitoring and controlling the placement process of HPC, including proper handling, transportation, and placement techniques to ensure that the concrete is placed and compacted correctly, avoiding issues such as segregation and honeycombing.

vi. Curing: Proper curing can ensure that the HPC reaches its full strength and durability potential by maintaining appropriate temperature and humidity conditions. Achieving high performance in concrete typically requires a careful selection of materials, precise proportioning, and meticulous curing techniques. Here are some curing methods, i.e., steam curing, moisture curing, spray curing, membrane curing, and internal curing, that can help in producing high-performance concrete. It's important to note that the specific curing method and duration may vary depending on the concrete mix design, ambient conditions, and project requirements. Consulting with a qualified engineer or concrete technologist is recommended to determine the most appropriate curing approach for achieving high-performance concrete.

Overall, these applied methods can be used alone or in combination to produce high-performance concrete with improved strength, durability, workability, and other desired properties. The popularity of applied methods in high-performance concrete (HPC) is driven by the significant benefits that HPC can offer in terms of strength, durability, and other desirable properties. However, to ensure that these methods are reliable and accurate, it is important to conduct rigorous analyses that evaluate their performance and compare them to traditional methods.

The accuracy of the methods used in producing high-performance concrete is crucial to achieving the desired properties of the concrete. The accuracy of the methods can be affected by various factors, such as the quality of the raw materials, the mixing procedure, and the curing process. Several testing methods can be used to evaluate the properties of the concrete, including compressive strength, tensile strength, and durability, to ensure accuracy. The properties can be measured through destructive testing, such as compression tests, or non-destructive testing, such as ultrasonic testing or penetration resistance testing.

Reliability-based analyses and accuracy performances

Reliability-based analyses can assess HPC structures' safety and durability under different loading and environmental conditions. These analyses consider uncertainties in the material properties, loading conditions, and other factors in evaluating the probability of failure or degradation over time.

One may evaluate accuracy performances through various testing methods, such as compressive strength, permeability, and durability tests. These tests can be used to validate the accuracy of the methods used to produce HPC and to verify that the desired properties have been achieved.

Comparison with traditional methods, validation criteria, and verification evidence

One may use a comparison with traditional methods to evaluate the effectiveness of HPC compared to conventional concrete. It may involve comparing the properties, performance, and cost of HPC and traditional concrete in various applications to determine the most suitable material for a project.

One may establish validation criteria to ensure that HPC meets the specific performance requirements of a given application. It may involve establishing minimum strength, durability, and other properties that must meet to ensure that the HPC performs as expected over its service life.

One may collect verification evidence through field monitoring and testing to confirm that HPC performs as expected in real-world conditions. It may involve monitoring the performance of HPC structures over time and comparing the results to predicted performance to ensure that the HPC meets its design specifications.

Overview on strength and durability

The strength of concrete against shaking loads depends on several factors, such as the type of concrete mix, the age of the concrete, the curing conditions, and the magnitude and frequency of the shaking loads. Concrete has high compressive strength that helps resist crushing under heavy loads but has relatively low tensile strength, making it susceptible to cracking under dynamic loads such as earthquakes. Engineers typically use reinforcing steel, such as rebar, to improve the seismic performance of concrete structures, which helps distribute tensile forces more evenly and prevent cracking. The reinforcement also helps transfer load from the concrete to the steel, taking advantage of the higher tensile strength of the steel. Hu et al. [15] said that while concrete can be designed to resist earthquakes, there is always some degree of uncertainty in predicting the exact response of a structure to a seismic event. Therefore, it's essential to incorporate safety factors into the design of concrete structures to account for this uncertainty and ensure the safety of the building.

One may modify the durability of high-performance concrete by incorporating different ingredients and changing the mix proportions. However, like all concrete, HPC can experience shrinkage, which refers to the reduction in volume or dimensions of the concrete due to various factors, such as drying, autogenous, and thermal shrinkage. Shrinkage in HPC can have implications on its durability, as it can lead to cracking, reduced service life, and other performance issues. The durability of high-performance concrete (HPC) with respect to chloride permeability is a critical factor in determining its resistance to chloride-induced corrosion of reinforcing steel, which is a common cause of deterioration in concrete structures exposed to chloride-containing environments, such as marine environments or deicing salt exposure. The following factors affect the durability of high-performance concrete:

i. Water-Cement Ratio: Lower the water-cement ratio, the higher the durability of the concrete. This is because a lower water-cement ratio leads to higher strength and denser microstructure, which results in better durability.
ii. Aggregate: Durable aggregates, such as quartz, granite, or basalt, can significantly enhance the durability of high-performance concrete. The shape and size of the aggregate also play a role in durability.
iii. Admixtures: Admixtures, such as superplasticizers, air-entraining agents, and corrosion inhibitors, can be added to high-performance concrete to improve its durability.
iv. Curing: Proper curing is crucial for ensuring the durability of high-performance concrete. This can be achieved by keeping the concrete moist and at a suitable temperature for a specified period.
v. Reinforcement: Reinforcement, such as steel or fiber, can enhance the durability of high-performance concrete by improving its crack resistance and reducing the risk of corrosion.

By making these modifications, high-performance concrete can be designed to be more durable and resistant to various environmental factors, such as freeze–thaw cycles, aggressive chemical environments, and abrasion.

Aim of study

The present paper reviews the literature on various aspects of high-performance concrete due to the effect of mineral and chemical admixtures. The study gives an overview of the current status of facts about using supplementary cementitious materials (SCMs) in HPC. The study has attempted the following:

- Identify the feasibility of SCMs with cement.
- Study the properties of HPC using mineral and chemical admixtures.
- Study the impact of elevated temperature on HPC.

Supplementary cementitious materials

Supplementary cementitious materials (SCMs) can be added to the concrete as a partial replacement for Portland cement, the main binding ingredient in concrete. These materials are often industrial byproducts that have cementitious properties. Wu et al. [16] suggested that the utilization of SCMs/mineral admixtures like silica fume (SF), rice husk ash (RHA), ground granulated blast furnace slag (GGBS), fly ash (FA), and limestone filler has a significant impact on concrete. Park et al. [17] discussed that by partially replacing cement, SCMs serve the primary goals of reducing material costs and the environmental impact associated with material manufacturing. Since the majority of SCMs come from plants or other naturally occurring resources, their use is well suited to this goal. It has also been demonstrated that increasing an SCMs dosage reduces CO2 emissions. Using SCM can conserve energy and resources, enhancing the resistance to permeation and aggressive chemicals. Menon et al. [18] said that incorporating the chemical admixtures like water reducers, retarders, accelerators, super-plasticizers, and air-entraining agents enhances the performance of concrete mix in terms of workability, strength, durability, etc. Applying SCM like GGBS and FA with SF and superplasticizer may be a prevalent technique to enhance concrete strength. Srivastava et al. [19] observed that after 28 days, SCMs increased the compressive strength of the concrete, and this happened because SCM particles serve as fillers and interact with the calcium hydroxide produced during the hydration of cement to produce calcium silicate hydrate (C–S–H). Some of the SCMs are the following:

Silica fume

Silica fume is a highly reactive mineral admixture that can significantly improve concrete compressive and tensile strength. It improves the resistance of concrete to chemical attacks, freeze–thaw cycles, and abrasion. It can reduce the water demand for concrete, resulting in enhanced workability and finishing. It contributes to the long-term strength and durability of concrete by reacting with the calcium hydroxide released from the hydration of cement to form additional cementitious compounds.

Fly ash

Fly ash is a byproduct of coal-fired power plants and is commonly used as a partial replacement for cement in the production of HPC. It can improve the strength development of concrete, particularly in the early stages. It can reduce the permeability of concrete, making it more resistant to water and chemical penetration. It can improve concrete workability and finishing ability, making it easier to place and finish. It can enhance the durability of concrete by reducing the potential for alkali-aggregate reactions, sulfate attack, and corrosion of reinforcing steel. It is a recycled material that can replace a portion of the cement in concrete, reducing the amount of energy and raw materials required for its production.

Ground granulated blast furnace slag

Ground granulated blast furnace slag is a byproduct of the iron and steel industry and is commonly used as a partial replacement for cement in concrete construction. It can improve concrete compressive and tensile strength, particularly in the long term. It can enhance the durability of concrete by reducing the potential for alkali-silica reactions and sulfate attacks. It can reduce the permeability of concrete, making it more resistant to water and chemical penetration. It can improve the workability and finishing properties of concrete. GGBS has a lower ignition temperature than cement, making concrete with GGBS more fire-resistant. However, using GGBS in concrete can also have some limitations, including variations in chemical composition and pozzolanic activity and the potential for variations in setting time and workability. It is essential to carefully evaluate the quality and suitability of GGBS for use in HPC.

Rice husk ash

Rice husk ash is a byproduct of the rice milling process and is known to have a high silica content. The use of RHA as a supplementary cementing material in concrete has been widely researched and has been found to have several benefits for HPC. The silica content in RHA reacts with the calcium hydroxide produced during the hydration of cement, forming additional calcium silicate hydrates. This results in an increase in the strength of concrete. The increased strength of concrete made with RHA helps to improve its durability and resistance to cracking, weathering, and chemical attack. The fine particles in RHA can improve the workability of concrete, making it easier to handle and place. Concrete made with RHA is suitable for use in sulfate-rich environments. However, it is essential to note that the use of RHA in concrete should be limited to certain proportions, as excessive amounts can adversely affect the strength of concrete and durability. The optimal proportion of RHA used in concrete should be determined through trial mixes and testing.

Characteristics of SCMs

Admixtures perform a significant role in the manufacturing of HPC. One of the necessary ingredients of the HPC is mineral admixtures [20]. They are utilized for various motives relying on their properties. Table 1 presents the various forms of mineral admixtures and their characteristics. Different materials having Pozzolanic properties like Silica Fume (SF), Rice Husk Ash (RHA), Fly ash (FA), Copper Slag, and Ground Granulated Furnace Slag (GGBS) are extensively used as the substitution for cement for making high-performance concrete [21–23]. The silica fume has a strength-improving effect on concrete because of the enhanced strength of the paste phase. At the interfacial transition zone, silica fume enhances the bonding of paste and aggregate particles, thus increasing concrete strength. Utilizing these admixtures boosts HPC's durability and strength features and is useful for throwing away commercial by-products that are hazardous to the environment.

Physical properties of SCMs

The physical properties of SCMs in HPC can vary depending on their composition and reactivity. However, they are generally lightweight and porous and improve concrete's

Table 1 Mineral admixtures used in HPC

Mineral Admixtures	Classification	Particle characteristics	Disadvantages
Rice husk ash	Highly active Pozzolana	Particles have a size of less than 45 µm and it has a porous and cellular structure	Variable quality, reduced early strength
Fly ash	Cementitious & Pozzolanic	It is available in powder form with a particle size of less than 45 µm, but 10% to 15% of particles are greater than 45 µm. It usually has a smooth surface and solid spheres	Slow strength development, transportation, and sourcing challenges
Silica fume	Highly active Pozzolana	It is found in the form of fine powder with an average diameter of 0.1 µm and contains solid spheres	High cost, increased setting time
Ground granulated blast furnace slag	Cementitious & Pozzolanic	It is found in the form of unprocessed materials like sand, which have a rough texture and are grounded to a size of less than 45 µm particles	Reduced early-age performance, increased water demand

strength, durability, and sustainability. Bulk density, specific gravity, fineness modulus, and color are all significant physical properties of SCMs. The findings of numerous investigations on the fundamental physical properties of SCMs are presented in Table 2. The process of calculating the weight of a sample change after it has been heated to high temperatures and some of its contents have burned or volatilized is known as a loss on ignition. Loss due to the ignition of SCMs might range from 0.20% to 5% of the total weight. SCMs have a specific gravity that ranges from 2.2 to 2.75.

Table 3 Chemical composition of SCMs

Properties (%)	SF	FA	GGBS	RHA [24]
Al_2O_3	0.25	27.98	12.35	0.85
CaO	0.33	1.70	31.82	1.94
Fe_2O_3	0.22	3.59	0.92	1.12
SiO_2	95.6	56.04	36.37	92.50
MgO	0.24	0.34	10.71	0.37
Na_2O	0.18	0.16	0.34	0.07
K_2O	0.31	1.06	0.46	3.25
TiO_2	0.15	2.03	0.60	0.05

Chemical composition of SCMs

The chemical composition of SCMs can impact the performance of HPC in several ways, including the setting time, air content, and pore structure of the concrete. For example, SCMs containing a high amount of iron oxide can help improve HPC's durability by reducing the permeability of concrete. The choice of SCM for a particular HPC mix will depend on the desired properties. Alkalinity is the ability of a material to neutralize acids and is essential for the durability of concrete. SCMs with high alkalinity help to reduce the risk of corrosion in concrete. Reactivity refers to the ability of a material to react with calcium hydroxide, a by-product of the hydration of cement, to form a durable and strong binder. Silica content is important in SCMs because it can contribute to forming silicate hydrates, which are responsible for the strength of concrete. The XRF study was carried out in the laboratory to determine the chemical properties of SF, FA, and GGBS, and the obtained results are presented in Table 3. The chemical properties of RHA are collected from the literature [24].

Chemical admixtures

Chemical admixtures are special ingredients added to concrete during mixing to enhance its properties and performance. These admixtures are typically added in small amounts and can modify the characteristics of fresh and hardened concrete. Various chemical admixtures, such as water-reducing, retarders, accelerators, super-plasticizers, and air-entraining agents, are widely used in HPC with a low water-binder ratio. Table 4 presents the functions of chemical admixtures. Chemical admixtures can be used in concrete in the state of liquid or solid. Still, the liquid admixture is preferable because it disperses quickly in the mixture. Nearly all water-reducing admixtures are anionic-based surfactants, which apply a repulsive force to the cement particles. As a result, the cement particles repel one another, and the flocculated structures deflocculate, as seen in Fig. 3. In this manner, the excess water that has been halted enters the mixture. Hence, to enhance the desired properties of concrete, water can be lowered to a specified percentage in the mix.

Multi-blended cement in HPC

The present study assesses noteworthy literature and checks the various aspects of HPC concerning how the materials are utilized in different ways and mean. In this paper, the utilization of materials is divided into the following categories: binary, ternary, and quaternary cementitious blends. This paper describes in detail how these cementitious blends are beneficial to enhancing the performance of HPC.

Binary blends

The binary blends refer to blended cement containing OPC and one SCM. In the combination, the cement is mixed with one of the mineral admixtures as the percentage replacement of cement. Kjellsen et al. [25, 26] evaluated the development of compressive strength of HPC and paste cubes with and without using silica fume (SF) for 1 to 4 years.

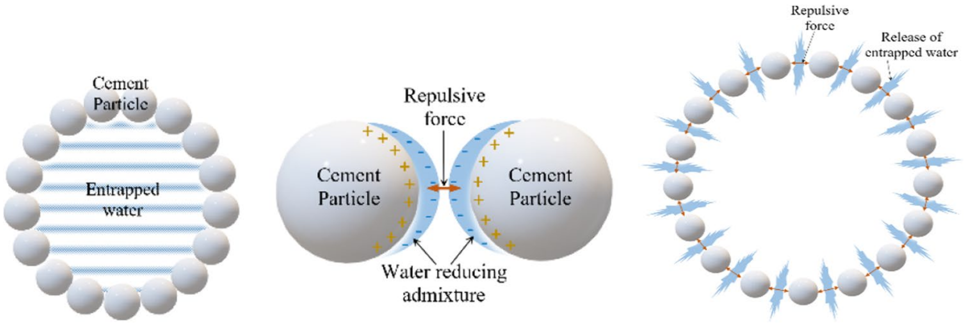
Table 2 Physical properties of SCMs (reproduced from References [16] & [24])

Properties	SF [16]	FA [16]	GGBS [16]	RHA [24]
Specific gravity	2.2	2.4	2.75	2.3
Bulk density (kg/m^3)	570	700	1200	150
Fineness modulus (m^2/kg)	20,000	290	400	2900
Color	Dark grey	Light grey	Whitish grey	Grey
Loss on ignition (%)	2.17	0.29	4.65	2.57

Table 4 Chemical admixtures used in HPC

Chemical admixtures	Function
Accelerator	To cut back the setting time of concrete, it is helpful in the early removal of formwork and thus utilize in low-temperature conditions concreting
Retarder	It is helpful to decelerate the cement hydration and it will prolong the setting time of cement and thus utilize in hot climatic conditions concreting
Plasticizer	To obtain good workability at a lower water-cement ratio for extensive strength, and it will be beneficial to save the cement
Super-plasticizer	To lower the need for water by 15%-30% without impressing the workability resulting in dense and high-strength concretes
Air-entraining agent	It is beneficial to enhance the workability after entraining tiny air bubbles in the mix that act like rollers. It is very imposing in freezing and thawing conditions. It supplies a crushing impact on the enlarging water within cold climate conditions concreting

Fig. 3 Mechanism of water-reducing admixtures



(a) (b) (c)

Bentur and Goldman [27] studied the bond-effect in high-strength concrete using SF. In both studies, the authors took the SF content as 0, 5, and 10% by weight of cement. After conducting the test at 1, 7, 28, 90 days, 9 months, 2 years, and 4 years, the authors observed that on day 1, the combination with SF had similar or lesser strength than the mix made without SF. While at 28 days and beyond this period, both concrete and paste mixtures with SF have superior strength to those without SF. The compressive strength of HPC is determined with the help of tests according to IS: 516 [28]. Figure 4 shows the compressive strength of HPC with various dosages of water/binder and silica fume. The maximum compressive strength is obtained at a w/b ratio of 0.25 with cement replacement by 10% of SF, which means higher strength can be achieved at a lower w/b ratio with an optimum dose of SF content.

HPC mixtures were prepared by substituting the cement content with 30% GGBS and fine aggregate particles with 20%, 40%, 60%, 80%, and 100% copper slag [29–31]. The workability and durability parameters like penetration of chloride ions and water absorption were estimated in the study. It is found that the chloride ion penetration decreases by 29.90% for 30% replacement of cement content with GGBS, and water absorption is reduced by 4.58%. From a workability point of view, the slump value rises by 60 mm to 85 mm for copper slag instead of 100% fine aggregate particles. The results show that compared to river sand, the water consumed by copper slag during mixing is significantly less. Rice husk ash (RHA) is the by-product of rice paddy. It contains non-crystalline silica and has a high probability of being utilized to replace cement in concrete.

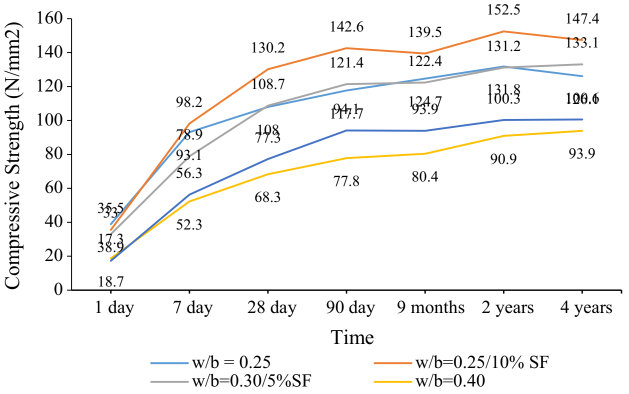


Fig. 4 Compressive strength of HPC with various dosages of water/binder and SF (reproduced from Ref. [25])

Studies were conducted to evaluate various replacement levels of cement with silica fume content as 0%, 2.5%, 5%, 7.5%, 10%, 12.5%, and 15% on durability properties and strength of HPC [32–34]. In the studies, M60 grades (water/binder = 0.32), M70 grades (water/binder = 0.30) & M110 grades (water/binder = 0.232) mixes are prepared to assess the high-performance concrete. The cement replaced with 10% silica fume shows the most promising performance in terms of compressive strength, tensile strength, flexural strength, water absorption, modulus of elasticity, and sorptivity. The gas permeability and compressive strength of HPC were determined considering the fly ash (FA) from 0 to 60% by replacing the cement [35–39]. The studies concluded that the use of fly ash could reduce the heat of hydration, improve workability and reduce the permeability of water, chloride, and greenhouse gas to concrete. The study used nitrogen gas as a permeating medium, and the Hagen-Poiseuille equation was employed to determine the gas permeability. The higher value of gas permeability is obtained at 60% cement substitute with FA and a water/binder ratio of 0.30 and the compressive strength at 0.25. It is found that the high-performance concrete with fly ash has higher gas permeability than the control HPC.

Mazanec and Lowke [40] & Mazanec and Schiebl [41] evaluated the constituent features of HPC. The authors used quartz flour & silica fume (SF) to prepare the HPC mix. Chopin et al. [42] analyzed the concrete composition effect using a mixing time of 240 s and a tool speed is 2.9 m/s. The required mixing time is analyzed by supplying the power to the mixing tool during the mixing process. After germinating, the tool speed from 1.4 m/s to 2.9 m/s often decreases the stabilization time by 11%, and a four times higher speed leads to a deficiency of roughly 16%. Several studies were conducted on the corrosion-reinforced HPC by utilizing calcium nitrite corrosion inhibitor (CNI) and fly ash [43–46]. The concrete having a w/c ratio of 0.29 with CNI at a rate of addition of 12.5 l/m^3 is observed to be superior in reducing the effect of chloride-stimulated corrosion of steel reinforcement. To determine the compressive strength of HPC, the concrete mixes were prepared for various cement replacement percentages with SF at different water/binder ratios [47–51]. The silica fume (SF) content taken is 0%, 10%, 20%, and 30% of the weight of the cement. Compared to that type of concrete prepared with SF, the increment of compressive strength of concrete much more depends on the decrement of water/binder ratio. The compressive strength of HPC increases in the case of substituting the cement with SF up to 20% compared to normal concrete.

Martins and Akasaki [52] & Olivares and Barluenga [53] examined the compressive strength of HPC added to tire rubber, which is derived from waste tires that are incredibly harmful to the environment. The cement is partially substituted with silica fume (SF), and tire rubber replaces the fine aggregate. The tire rubber fibers replace the sand with 3% of its volume. The compressive strength evolution of the HPC with rubber fibers remained in the same order as in HPC without rubber fibers. It is found that the tire rubber fibers reduce the slump value of HPC. The HPC with rubber fibers has more ductility than without rubber fibers. Kamble [54] & Sakthivel et al. [55] conducted an experimental study comparing the strength of normal concrete with HPC, utilizing crushed sand and river sand. In the study, the fine aggregate is replaced entirely by the stone quarry dust to prepare the mixes of M20 and M25 grades of concrete. The compressive strength of the M20 grade of concrete made with stone dust is nearly the same as that of a mix prepared with river sand. But in the case of M25 grade of concrete, that is slightly higher when using stone dust as compared to using river sand. The study concluded that the stone dust could completely replace the river sand with fly ash and super-plasticizer to obtain high strength and workability. The utilization of stone dust is economical in large-scale projects. Joshi [56] discussed the microstructure and strength of high-performance concrete. The incorporation of silica fume is very profitable because it has very fine particle in size and fills the pores of the concrete. SF reacts with calcium hydroxide & produces the calcium silicate hydrates (CSH) gel during the cement hydration, and CSH gel is principally responsible for developing the strength of concrete. Physical or chemical effects often impair durability. If the microstructure is very dense with few capillary pores, adding silica fume can improve the resistance against the impact. Such types of concrete can protect the reinforcement against corrosion.

Based on the review of a good amount of literature above, this paper outlines some of the following remarks on binary cementitious blends, which may be considered for study in the future.

- Almost all the researchers have used SF, GGBS, and FA alone to replace cement in binary blends. But, materials like rice husk ash (RHA), metakaolin, sludge powder, etc., are limited in use to replace cement as a single mineral admixture.
- Not much literature is available to check the sorptivity of high-performance concrete.
- Earlier, most researchers had concentrated only on strength, not durability.
- Lack of information on application-based high-performance concrete using multi-blends cementitious materials.

Ternary blends

The ternary blends contain OPC and two other SCM in the binder, blended at the cement or batch plants. In the mix, the cement is used with two mineral admixtures as the percentage replacement of cement. Tamimi [57] studied the impact of replacement materials at different levels and got the optimum mix with extreme safety adverse to acid attacks. Different combinations of pulverized fly ash (PFA) with fix amount of silica fume of 10% were used to replace the cement in the studies [58, 59]. When the specimens were fully immersed in 1% of the sulphuric acid solution, they took almost eight weeks to lose 20% of their weight in the control mix and took thirteen weeks to lose 20% of their weight while together with 10% silica fume and 60% pulverized fly ash. Whereas in 1% of the hydrochloric acid solution, it took six weeks to lose 20% of its weight in the control mix and thirteen weeks to lose 20% of its weight together with 10% SF and 60% PFA. This study addressed that a mix of 60% PFA and 10% SF as a normal hydraulic cement substitution would produce maximum protection against acid attacks. HPC mixes were produced to test their performance in seawater and severe sulphate environments ($MgSO_4$ & Na_2SO_4) [60–62]. Mixes contain various proportions of silica fume (0, 2, 40, 60 kg/m^3) and natural pozzolana (0%, 5%, 10%. 15% by weight of cement). After storing the specimens for one year, concrete mixes were investigated. The results show that the combination containing 15% of SF and 15% of natural pozzolan has provided superior safety in seawater and sulphate solutions.

A comparative study was conducted to check the compressive strength and the resistance against the attack of H_2SO_4 [63–66]. The study administered the characteristics of high-volume fly ash concrete (HFAC), having 40% of FA, Portland cement concrete (PCC), and concrete having a combined quantity of 15% GGBS and 25% fly ash (GGFAC). In terms of resistance to H2SO4 attack, GGFAC is found to be superior to both PCC and HFAC. The compressive strength of HFAC and GGFAC increases with the submergence period in sulfuric acid solution. Table 5 presents the compressive strength of HPC from day one to the year. Figure 5 shows the development of the compressive strength of the concrete cube with time. More interestingly, the HFAC mix has maximum compressive strength, which is increased by 64.30% between 28 days to 1-year curing period; however, it has a lower value than PCC and GGFAC up to 28 days curing period.

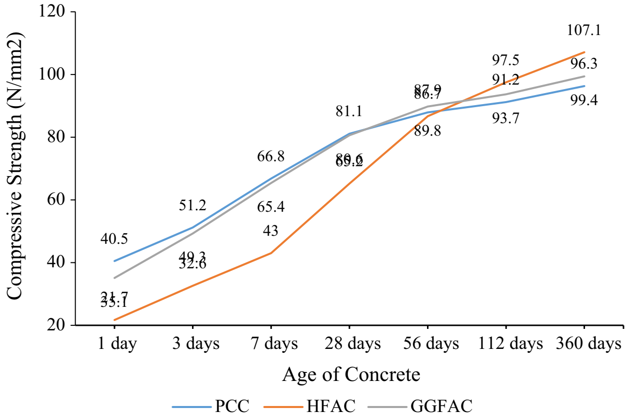


Fig. 5 Compressive strength of HPC (reproduced from Ref. [63])

A glass fiber reinforced high-performance concrete (GFRHPC) mix containing various percentages (0%, 0.5%, 1%, 1.5%) of glass fiber and various percentages (0%, 10%, 20%, 30%) of fly ash (FA) was prepared for investigation [67–70]. The water-binder ratio used was 0.35. Specimens were cast and analyzed to determine the value of tensile and compressive strength. The workability was measured by conducting the compacting factor test. It is observed that maximum tensile and compressive strength is achieved using 1% glass fiber and 10% FA. The workability of GFRHPC mixes decreases with the increment of fly ash. Several studies were conducted to analyze the carbonation, gas permeability, and compressive strength of HPC using GGBS or FA [71–74]. The water-binder ratio between 0.25 to 0.35, and M-100 naphthalene-based Na_2SO_4 super-plasticizer dosage ranges from 0.6% to 1.8% was used. The mixes are prepared with various substitution dosages of GGBS and FA, and they are 0%, 15%, 30%, 45%, and 60%. Compared to control concrete, the mixtures prepared with up to 30% FA at small water-binder ratios enhanced the compressive strength. The results show a slight increment in both carbonation depth and gas permeability. While at higher water-binder ratios, it goes down significantly.

Muthupriya [75] investigated the behavior of short columns made of HPC. Seven mixes are prepared with silica fume of 0%, 5%, 7.5%, 10%, and fly ash of 10% to study the mechanical properties of HPC. The mix with 7.5% silica fume shows a higher value of ultimate capacity, which is 21.4% higher than the control mix, and it shows ductile behavior. The mix for columns made with 10% FA and 5% SF offers a higher value of ultimate capacity, which is

Table 5 Compressive strength of HPC (reproduced from Reference [63])

Binder combination	Compressive strength of cube (N/mm^2)							Strength gain from 28 days to 1 year (%)
	1 day	3 days	7 days	28 days	56 days	112 days	360 days	
PCC	40.5	51.2	66.8	81.1	87.9	91.2	96.3	18.7
GGFAC	35.1	49.3	65.4	80.6	89.8	93.7	99.4	23.3
HFAC	21.7	32.6	43	65.2	86.7	97.5	107.1	64.3

14.7% more than the control mix. The mix for the columns prepared with SF of 10% and FA of 10% shows higher stiffness. Silica fume is a pozzolanic material commonly used with other additives in high-performance concrete (HPC) to improve its mechanical and durability properties. When silica fume is added to concrete, it reacts with calcium hydroxide, produced during the hydration of cement, to form an additional calcium silicate hydrate (C-S–H) gel [76–78]. Prajapati et al. [79] & Andriya and Priya [80] conducted experimental studies on HPC using FA and GGBS of M60 grade of mix to examine the flexural strength, compressive strength, and split tensile strength. GGBS replaced the cement at 10%, 15%, and 20%, and FA at 10%, 20%, and 30% in the study. The various dosages of 10%, 20%, and 30% foundry sand substituted the natural sand. The higher compressive strength is obtained when the concrete mix contains 10% GGBS and 30% foundry sand. The maximum split tensile strength of HPC is obtained when the concrete mix has 20% GGBS and 30% foundry sand. The maximum flexural strength of concrete is obtained when the mixture has 10% GGBS and 10% foundry sand. In all mixes, compressive strength is found to be less at 14 days, but it is high at 28 days because of the amalgamation of FA and GGBS.

A few studies were focused on compressive strength, durability, use of admixture, advantages and disadvantages of HPC [81–83]. The compressive strength of HPC made of finer sand is more than the natural gradation sand. The authors examined the concrete mix based on long and short-term testing techniques for controlling HPC's quality and design. Silica fume (SF) reduces permeability. The authors used different dosages of FA and SF (0%, 10%, 20%, and 30%) to study compressive and flexural strength. Autoclave curing enhances flexural and compressive strength by 30.3% and 37.5%, respectively. The impact of factory by-products on the behavior of HPC was analyzed in the studies [84–86]. The studies investigated the function of silica fume (SF) as cement replacement on flexural, compressive, and split tensile strengths and permeability parameters. The concrete mixes contain 0%, 5%, 7.5%, and 10% SF and a stationary quantity of 10% FA. Silica fume strongly affects compressive strength at the age of 7 days, 28 days, and 90 days. Fresh concrete containing SF and FA is more cohesive and less susceptible to segregation. After testing the concrete specimens, the compressive strength of HPC with 7.5% of silica fume obtained is 12.18% higher than normal concrete, and the flexural strength is 29.8% more. The split tensile strength of HPC is 17.06% above the normal concrete.

Mondal and Banerjee [87] experimentally investigated the HPC of M60 grade using both chemical and mineral admixtures. The water-binder ratio ranges from 0.32 to 0.35, and a super-plasticizer is CONPLAST-SP 430. FA and SF are utilized as mineral admixtures. Concrete specimens are prepared to obtain the compressive strength and split tensile strength at 7 days and 28 days of the curing period. It is observed that the concrete has high fluidity, strength, and durability at 30% of SF and FA. Two waste materials, i.e., class F fly ash and recycled concrete aggregate, were used to prepare a high-performance concrete mix [88–91]. The concrete cubes of size 150 mm are prepared using 10% metakaolin and 16.7% fly ash of the total mass, cured according to PN-EN 12,390–2 code. The authors suggested that it is possible to manufacture a high-merit concrete of 55 MPa average compressive strength at the duration of 28 days of curing, and it can often be more than 60 MPa after 90 days. The sorptivity value and chloride migration coefficient are considered for testing the concrete cubes for categorizing them as decent-quality concrete out of the analyzed mixes. The carbonation depth measured is 8 mm after 28 days of casting for the most examined concretes. The split tensile strength varies from 1.36% to 25.28% between 28 and 90 days. The concrete is more durable if the sorptivity is less. Table 6 presents the durability classification of HPC based on the sorptivity value.

Salim and Prasad [92] studied the HPC properties utilizing mineral admixtures and foundry sand. The foundry sand is the industrial waste material used to make the HPC as a fractional substitution of fine aggregate. The utilization of foundry sand reduces workability. The compressive strength increases with the foundry sand up to the substitution level of 10% to 30% of fine aggregate. After replacing the fine aggregate with foundry sand, the silica fume concrete mix shows a decrement in split tensile strength and flexural strength, raising the percentage change in used foundry sand. Wang et al. [93] studied the manufacturing of ultra-high-performance concrete with raw materials and common technology, water-binder ratio, the influence of cementitious binder content, limestone powder, and GGBS as the replacement of cement. Ranjitham et al. [94] determined HPC properties for the M75 grade design mix using fly ash and GGBS. The workability is evaluated using the slump test as per IS: 1199 [95]. The slump values with various dosages of foundry sand are illustrated in Fig. 6. Seshadri and Salim [96] studied the properties of HPC of M60 grade mix with SF. In the case of SF, the mix prepared with 0% foundry sand shows the maximum slump value of 140 mm and is more workable.

Ternary blends using Pozzolanic materials can be a better option for constructing concrete structures. The utilization of

Table 6 Classification of concrete durability based on the sorptivity value (reproduced from Reference [88] with minor modifications)

Sorptivity (mm/$s^{0.5} \times 10^{-3}$)	Class of concrete durability				
	Very low	Low	Middle	High	Very high
	> 62	62–33	33–20	20–8.33	< 8.33

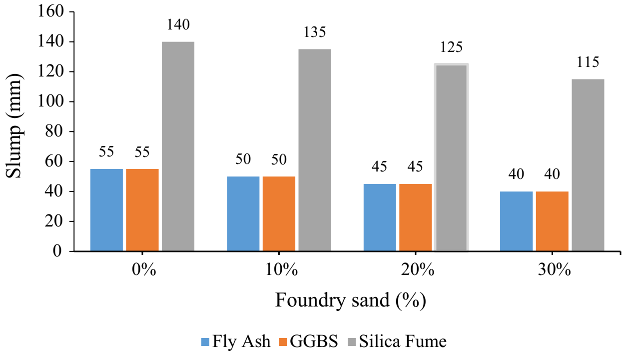


Fig. 6 Slump with various dosages of foundry sand (%) (reproduced from Ref. [96])

industrial wastes can reduce cement consumption, and it will help reduce carbon dioxide emissions. High-performance ternary blended cement can be prepared by adding coarse supplementary cementitious materials and fine ground granulated blast furnace slags into ordinary Portland cement.

Based on the aforementioned significant literature review, the present study summarizes the following observations on ternary cementitious blends for future scope.

- There is less use of ternary blends in actual construction.
- There are no Indian Standards for the design mix of such blends.
- The investigation needs to comprise some basic studies investigating the minerals configured during the ternary blend hydration reactions.

Quaternary blends

The quaternary blends contain OPC and three other SCM in the binder. The cement is used with three mineral admixtures as the percentage replacement of cement in the mixture. Numerous studies were conducted to discuss the modulus of elasticity and compressive strength of HPC for four different types of combinations under three various forms of curing systems of temperatures between 20 °C to 50 °C [97–101]. The materials used are FA, GGBS, SF, Type-I Portland cement, fine sand, and crushed stone aggregate. The methods of curing used in the study were: wrapped curing (WRC), water curing (WC), and dry air curing (DAC), are employed. The maximum age for curing is taken as 91 days, and curing temperatures are taken as 20 °C, 35 °C, and 50 °C. Under the wrapped curing condition, the compressive strength is found to be superior to dry air curing conditions at an early age. It signifies that the employment of SF at moderate temperature will increase strength and durability. Under the wrapped curing system and at 20 °C temperature, the dynamic modulus of elasticity raises continually, but it decreases under the dry air curing system at the age of 28 days curing period. However, at 56 and 91 days, SF and FA concrete show a greater value of dynamic modulus of elasticity. It has been found that silica fume disintegration begins within one day, followed by the manufacture of silica-rich gel within seven days and final alteration into dense C-S–H gel at 28 days. Tables 7 and 8 present the modulus of elasticity and compressive strength under various temperatures and curing conditions.

Elahi et al. [102] & Khatri and Sirivivatnanon [103] investigated the mechanical properties and durability of HPC. Concrete mix prepared by utilizing SCM, i.e., FA, GGBS, and SF. The cement substitution is made with up to 70% GGBS, 15% SF, and 40% FA. To resist the chloride diffusion, the ternary concrete mixes containing 7.5% SF and 50% GGBS or FA show superior resistance among all the concrete mixes. In the case of 7.5% SF, the strength development is superior to other supplementary cementitious materials. In the case of sorptivity, the binary mixes containing 50% GGBS and 20% FA are found beneficial in comparing the control mix. Chinaraju et al. [104] reviewed the impact of SF, FA, and GGBS on HPC. The replacement levels of Portland cement with silica fume are 2.5%, 7.5%, 10%, & 12.5%, with fly ash are 10%, 20%, & 30% and with GGBS are 10%, 20%, & 30%, by the weight of cement. The combination of 10% SF and 10% FA is found to be superior. It shows the highest compressive strength, and there has been an increment of 15.64% and 13.24% at 7 days and 28 days of curing age. The split tensile strength increases moderately for various combined mixes of GGBS and FA with 10% SF. There is limited variation in flexural strength for many of the combined mixes, but flexural strength declines at a higher rate besides the utilization of 10% silica fume. Lakshmi et al. [105] analyzed the physical properties of HPC containing FA and SF along with the glass fibers. Silica fume with various dosages of 0%, 5%, 7.5%, 10%, and 12.5% is used as a partial substitution of cement by weight, 10% of fly ash is used with various dosages of SF, and 0.3% of glass fibers are used to manufacture the HPC mixes. The optimum compressive strength is obtained with 0.3% glass fiber and 10% SF mix at 28 days of curing, and it has been 1.13 times higher than the control mix. The maximum compressive strength is obtained with 0.3% glass fiber, silica fume of 10%, and fly ash of 10% mix at 28 days of curing, and it is 1.17 times more than the normal concrete mix. The split tensile and flexural strength get a higher value with the same dosage of SF, FA, and glass fiber.

Malik [106] & Alsalman et al. [107] presented the preparation, types, working, usage, and development of HPC. The authors discussed the addition of chemical and mineral admixtures to get a higher performance of concrete. HPC gives better performance in terms of load, durability, behavior, and environmental conditions. The authors suggested that the utilization of HPC leads to enhancing the

Table 7 Compressive strength values under various temperatures and curing conditions (reproduced from Reference [97])

Category of mixes	Temperature of curing (°C)	Methods of curing	Compressive strength (MPa)			
			7 days	28 days	56 days	91 days
NPC	20	WC	85	105	114	119
		WRC	85	103	116	125
		DAC	71	74	83	81
	35	WRC	89	107	104	115
		DAC	72	74	78	77
	50	WRC	86	112	102	110
		DAC	70	73	70	78
GGBS	20	WC	85	119	119	127
		WRC	92	113	113	120
		DAC	65	77	74	78
	35	WRC	104	112	115	123
		DAC	71	77	76	80
	50	WRC	111	108	112	114
		DAC	76	72	81	84
SF	20	WC	93	123	118	130
		WRC	91	124	123	128
		DAC	73	93	92	97
	35	WRC	106	126	126	130
		DAC	80	97	98	95
	50	WRC	111	116	100	113
		DAC	87	87	91	93
FA	20	WC	99	107	120	121
		WRC	97	108	112	111
		DAC	82	86	92	94
	35	WRC	113	125	114	131
		DAC	93	100	95	98
	50	WRC	108	125	116	110
		DAC	93	95	93	96

strength of any concrete more than normal concrete. Incorporating 5% silica fume and 30% fly ash gives long-term strength to HPC. Laskar and Talukdar [108] studied the effects of mineral admixtures on the rheological properties of HPC. The yield stress of concrete decreases when there is an increase in cement replacement with RHA and FA. Also, SF is the better material for the plastic viscosity required for HPC design. The present study outlines the following remarks on quaternary cementitious blends for further research based on the literature review mentioned above.

- There is scanty literature available on quaternary blends made by combining three mineral admixtures.
- Most researchers have focused on compressive strength, split tensile strength, flexural strength, and modulus of elasticity, but there is a lack of study on other parameters like workability, segregation, bleeding, permeability, and acid attacks.
- There is no design code for the mix of quaternary blends.

Alternatives for manufacturing of HPC

Many efforts have been put forward in developing the HPC for building structures with enhanced performance and safety. Many other products like copper slag and quartz flour are used as fine aggregate replacements. Sierens et al. [109] discussed the feasibility study on recycled aggregates to develop ultra-high-performance concrete. It is another way to get HPC having superior mechanical and durability properties and good workability. Corominas et al. [110] compared the structural behavior of prestressed concrete sleepers prepared with high-performance recycled aggregate concrete (HPRAC) and HPC, where natural aggregates were replaced with recycled aggregate. The results show the satisfactory performance of the HPRAC-50 and HPRAC-100, which are close to that of the HPC sleepers. Hwang et al. [111] investigated the impact of the use of lightweight sand (LWS) and moist curing on the mechanical properties of HPC. The water-Cement ratio of 0.3 & 0.4 and substitution rates with LWS

Table 8 Modulus of elasticity under various curing conditions and temperatures (reproduced from Reference [97])

Category of mixes	Temperature of curing (°C)	Methods of curing	Modulus of elasticity (× 10^4 MPa)			
			7 days	28 days	56 days	91 days
NPC	20	WC	4.69	5.04	5.14	5.27
		WRC	4.88	5.05	5.10	5.23
		DAC	4.22	4.38	4.27	4.17
	35	WRC	4.78	4.88	4.96	4.99
		DAC	4.19	4.13	4.10	4.02
	50	WRC	4.73	4.91	4.82	4.65
		DAC	4.16	3.95	3.85	3.77
GGBS	20	WC	4.61	5.15	5.16	5.18
		WRC	4.65	4.86	4.97	4.80
		DAC	3.90	4.05	4.11	3.90
	35	WRC	4.74	4.88	4.75	4.94
		DAC	3.95	3.92	3.82	3.74
	50	WRC	4.85	4.80	4.55	4.37
		DAC	4.01	3.87	3.70	3.67
SF	20	WC	4.32	5.21	5.24	5.28
		WRC	4.78	5.07	5.16	5.22
		DAC	4.20	4.23	4.19	4.17
	35	WRC	4.89	4.82	4.84	4.84
		DAC	4.17	4.12	3.99	4.05
	50	WRC	4.75	4.65	4.48	4.45
		DAC	3.92	3.92	3.82	3.74
FA	20	WC	4.81	5.12	5.17	5.34
		WRC	4.86	5.10	5.15	5.26
		DAC	4.34	4.32	4.28	4.40
	35	WRC	5.00	5.00	5.15	5.20
		DAC	4.41	4.30	4.30	4.22
	50	WRC	4.96	4.97	4.71	4.66
		DAC	4.17	4.12	4.08	3.99

of 0% & 30% were adopted. The combined LWS (30%) and moist curing for 7 days show a maximum increase in compressive strength and maximum decrease in total shrinkage compared to the concrete of 7 days of moist curing without LWS. Guneyisi and Gesoglu [112] investigated HPC characteristics, indicating a high substitution level of slag under wet and air curing conditions. There is a reduction in strength after incorporating slag at 50% and higher at the early age of air-cured specimens, while the strength increases at 60% of slag incorporation for 90 days wet cured specimens. Yun and Jang [113] discussed the early age properties of HPC by embedded Fiber Bragg Grating (FBG) sensor. The authors monitored the high thermal deformation and autogenous shrinkage at an early age. The sensors are fixed inside the mould during the concrete casting to ensure the correct thermocouple and FBG sensor positions inside the specimen. It is found that from the first day, the deformation of the HPC mix increases rapidly and attains a higher value. The deformation (57 με) on the first day is about 35% of that on the 14th day (165 με). The higher deformation value must be addressed, obtained on the first day, regarding the permeability and durability of HPC.

Jabri et al. [114] examined the impact of copper slag on high-performance concrete as the replacement of sand ranging from 0 to 100%. There is a slight rise in the HPC density, nearly 5% when mixed with copper slag compared to the control mix. The use of copper slag up to 50% gives maximum compressive strength. The compressive strength decreases beyond 50% of replacement because of free water content within the mix. After replacing the sand with 80% and 100% copper slag, these mixes give insufficient compressive strength. The authors suggested that copper slag can replace 40% of sand by weight to obtain suitable properties of HPC. Choudhary et al. [115] focused on the recent developments in HPC and discussed the effects of mineral and chemical admixtures and the advantages and drawbacks of HPC over conventional concrete. The study addresses design inadequacies, poor construction practices, environmental degradation, increased loads on the structure because of high-rise buildings, and unexpected seismic loading conditions. Zhutovsky and Kovler [116] discussed the internal curing technology used to reduce cracking potential and autogenous shrinkage in HPC. The utilization of internal curing in concrete mixes prepared with a low water/cement ratio should be lower than 0.30, resulting in a reduction in drying shrinkage and cracking sensitivity. By decreasing the cracking sensitivity of concrete mix, internal curing capacity increases with the water/cement ratio shortage. Internal curing adversely affects HPC's compressive strength at an early age but diminishes with time. Similar data are observed for durability, tensile strength, and flexural strength. However, the effect of internal curing in hardened concrete is insignificant.

Effect of Elevated Temperature on HPC

When HPC is exposed to high temperatures, the chemical and physical processes that contribute to the strength of the concrete are altered. A few studies were conducted to evaluate HPC's microstructure and compressive strength at a very high temperature [117–119]. The authors measured the pore size distribution and variation in the porosity of concrete by the mercury intrusion porosimetry (MIP) technique. Figure 7 and 8 illustrate the compressive strength and porosity before and after exposure to high temperatures, respectively. When exposed to high temperatures, the compressive strength of HPC reduces much more than the normal concrete. However, the porosity of HPC increases more than the normal concrete. Mundhada and Pofale [120] examined that elevated temperature mainly impacts compressive strength. Despite the well-known ability of concrete to resist fire, a sizable loss of mechanical characteristics may occur. The testing carried out by some researchers includes early research on the impact of fire on the behaviour of concrete with compressive strength of more than 40 MPa. They conducted tests up to 1600 ^{0}C temperature, using lightweight aggregates (LWA) and Normal weight aggregates (NWA) (carbonate and siliceous) to cast the specimens. Cylindrical specimens of 75 mm in diameter and 150 mm high were tested. Up to 350 $^{\circ}$C, no explosive spalling was noticed. After 350 $^{\circ}$C, the majority of the compressive strength of specimens gradually dropped. Shah et al. [121] investigated numerous studies on the compressive strength of HPC and found a significant but progressive strength decline at 350 °C and a dramatic decrease after that. Table 9 reproduces the results of various literature on elevated temperature.

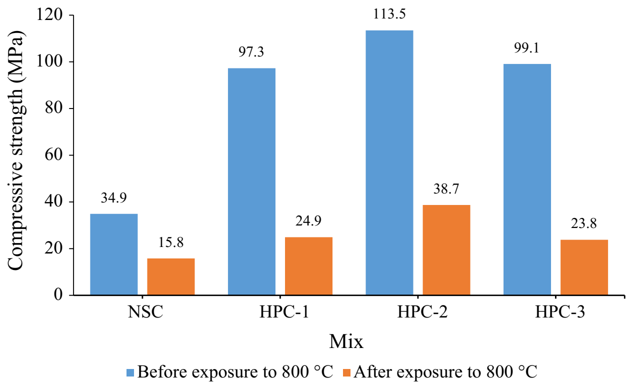


Fig. 7 Compressive strength before and after exposure to high temperature (reproduced from Ref. [117])

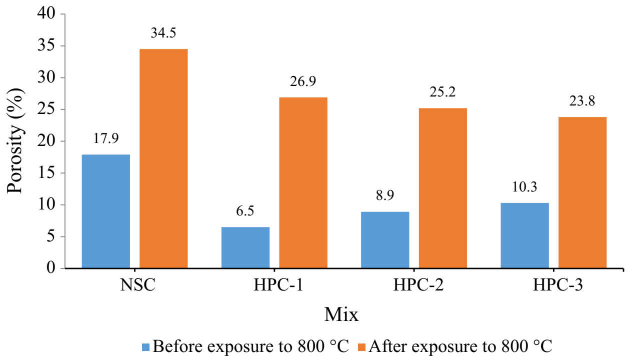


Fig. 8 Porosity before and after exposure to high temperature (reproduced from Ref. [117])

According to ACI-318 [122], high-performance concrete is a type of concrete mix that provides remarkable performance to any structure. The consistency requirements are impossible to obtain by utilizing 0traditional materials, standard mixing, casting, and curing exercises. Strategic Highway Research Programme (SHRP) suggests one of the subsequent needs of high-performance concrete, which is helpful in the construction industry. Cube samples were prepared to determine the residual fracture energy for ordinary gravel concrete, high-performance basalt concrete, and concrete behavior at high temperatures [123–125]. Samples were heated to a specific maximum temperature at 1 $^{\circ}$C/min and kept at this temperature for about 8 h before cooling to room temperature and tested considering the three-point loading. For both types of concrete mixes, the residual fracture energy increases impressively by about 50% after exposure to 300–400 ^{0}C temperature than the control value at room temperature.

Applications and limitations of HPC

HPC is used in various applications where high strength, durability, and low maintenance are desired. Some of the common areas of application are:

- Bridges and Overpasses

Table 9 Early studies on HPC under elevated temperature (reproduced from Reference [121])

S.no	Name of researchers	Test method	Material type	Compressive strength (MPa)	Temperature at explosive spalling observed (°C)
1	Abrams	Stressed, Unstressed, Unstressed residual	LWA and NWA	23–45	350
2	Diederichs et al	Unstressed	OPC, SF, Fly Ash, GGBS	33–114	350
3	Castillo	Stressed, Unstressed	OPC	28–62	320–360
4	Sullivan et al	Unstressed, Unstressed residual	OPC, GGBS, SF	38–65	350–400
5	Hammer	Unstressed	SF with LWA and NWA	69–118	300

- Tall Buildings and Skyscrapers
- Nuclear Power Plants and Dams
- Offshore Structures
- Runways and Taxiways in airports
- Wind Turbine Towers
- Industrial flooring and heavy-duty pavements
- Seismic-resistant structures
- Rapid repair and rehabilitation of existing structures

HPC has high compressive and tensile strength, making it ideal for use in bridges and overpasses that need to withstand heavy loads and environmental stresses. HPC has low permeability, making it less susceptible to environmental exposure and chemical attack damage, thus increasing its service life. HPC can also be designed with improved seismic resistance, making it ideal for earthquake-prone areas where bridges and overpasses are exposed to seismic forces. The reduced permeability of HPC results in lower maintenance requirements, reducing the long-term costs associated with building maintenance. Breitenbiicher [126] examined that the use of HPC can also result in the ability to build taller and more slender buildings, thus maximizing the use of available land and improving the aesthetic appeal of the building design. HPC has improved workability, making it easier to handle, place, and finish, thus reducing construction time and improving productivity. HPC can also be designed with radiation shielding properties, making it ideal for nuclear power plants where radiation protection is a critical design requirement. The use of HPC can also improve these structures' safety and reliability, which are crucial for the safe and efficient operation of these facilities. HPC can also be designed with increased fatigue resistance, making it ideal for offshore structures subjected to repetitive loads and stress cycles. HPC can also be designed with increased fatigue resistance, making it suitable for wind turbine towers subjected to repetitive loads and stress cycles from wind forces. Shahri et al. [127] said that the geotechnical subsurface conditions in engineering projects provide particular difficulties, yet the best outcomes can be obtained by building detailed 3D geographic models. This suggests that investigating other approaches and figuring out the limitations of the modeling procedure and data shortages are still crucial areas for investigation. Over the past ten years, different facets of geotechnical modeling have undergone considerable advancements due to the development and capabilities of computer visualization through AI and soft computing techniques. In order to build high-rise structures, HPC is often used. It has been employed in parts like foundations, shear walls, and columns (particularly on lower levels where the loads will be the largest). In bridge construction, HPC is also utilized. Before going for construction, we have knowledge of soil surface conditions. Ghaderi et al. [128] considered the use of 3D modeling to define soils using a combination of artificial intelligence techniques. They used a hybrid GFFN-GA model to present a 3D-categorized soil. The proposed method and created GFFN-GA model were intended to contribute to a novel use of a 3D view in field geo-engineering, which was shown to be an effective and sufficient tool to estimate soil layers in unsampled areas.

High-performance concrete (HPC) is a type of concrete that is engineered to possess superior strength, durability, and other performance characteristics compared to conventional concrete. The application of HPC can greatly impact its strength and durability. Here's how:

i. Strength: The primary characteristic of HPC is its high compressive strength. The application of HPC involves using carefully selected and proportioned materials, including cement, aggregates, and admixtures, to achieve a higher strength compared to regular concrete. HPC is designed to have a higher strength at early ages, which allows for faster construction and reduced curing times. The use of high-quality materials, precise mixing, and curing methods during application are crucial in achieving the desired strength of HPC.

ii. Durability: HPC is known for its superior durability compared to regular concrete. The application of HPC typically involves using low water-to-binder (w/b) ratios, which results in denser and more impermeable concrete. It reduces the ingress of harmful substances, such as chlorides and sulfates, which can cause corrosion of reinforcing steel and other durability issues. Additionally, the use of high-quality aggregates and carefully selected admixtures in HPC can enhance its durability by improving resistance to freeze–thaw cycles, abrasion, and chemical attacks.

HPC offers enhanced properties compared to regular concrete but has certain limitations that can impact its applications. These limitations include cost, mix design complexity, availability of materials, workability and curing time, testing and quality control requirements, structural design considerations, construction practices, and expertise. It is important to carefully consider these limitations when considering the use of HPC in specific applications and plan accordingly to ensure successful implementation. HPC has some following limitations:

- A thorough quality check is necessary since this concrete is frequently used to build enormous constructions.
- Due to the usage of a number of admixtures and premium ingredients, the initial costs are typically considerable.
- Produced and placed with care.

Advantages, disadvantages, and challenges of HPC

HPC is a type of concrete that is designed to have improved strength, durability, and sustainability compared to traditional concrete. The following are some of the main advantages of using HPC:

- Reduction in the quantity of concrete and construction time.
- Reduction in self-weight of the structure.
- Superior durability and long-term performance.
- High resistance to crack propagation and chemical attack.
- Ability to withstand large column loads.

Despite various advantages, HPC has some disadvantages, and are as follows:

- Requirement of the heavy initial cost.
- No discussion on the combination of SCMs for designing the mix.
- No specific standards or codal provisions for the design mix of HPC.

The use of HPC presents several challenges that must be overcome in order to achieve its full potential. Some of the main challenges in the use of HPC include the following:

i. Cost: HPC is often more expensive than traditional concrete due to the use of high-quality raw materials and specialized production methods. This can make HPC less attractive for cost-sensitive projects and limit its widespread use.
ii. Complex Mixture Design: HPC requires a precise and complex mixture design, which can be challenging for concrete producers unfamiliar with HPC. This can result in inconsistent quality and performance of HPC and limit its widespread adoption.
iii. Lack of Standardization: The lack of standardization in the production and use of HPC can lead to inconsistent quality and performance and create difficulties in the design and construction process.
iv. Limited Testing: The limited availability of testing facilities and standards for HPC can make it difficult to assess its performance and potential fully and can limit its use in specific applications.
v. Durability: While HPC is designed to have improved durability, its long-term performance still needs to be better understood. More research is required to assess its potential fully.

Sensitivity and uncertainty analyses on HPC

Sensitivity and uncertainty analysis are two important methods used in designing and assessing HPC. Sensitivity analysis is a method that evaluates the effect of changes in input parameters on the output results of a model. In the context of HPC, sensitivity analysis is used to determine which variables impact the concrete mixture's performance. This information can be used to optimize the mixture design and improve the overall performance of the concrete. On the other hand, uncertainty analysis assesses the variability and error in the input data and model assumptions. In HPC, uncertainty analysis is used to determine the range of possible values for the performance of the concrete, given the variability and error in the input data and model assumptions. This information can be used to make informed decisions about the design and use of HPC. In HPC construction, sensitivity and uncertainty analyses are very helpful in decreasing the risk of process in modeling, mixture design, and construction practices. Asheghi et al. [129] successfully created and examined two predictive artificial neural network-based models for three rivers suspended and bed loads. These models examined the channel geometry, geomorphological aspects, and hydraulic characteristics utilizing nine input parameters. Before using the sensitivity analysis techniques, it was seen that the best performance fell from 11 and 12 neurons to 6 and 8 neurons, respectively. Razavi et al. [130] observed that the mathematical modeling would soon be wholly dependent on sensitivity analysis. However, sensitivity analysis still has a great deal of untapped potential for developing mechanistic and data-driven models of natural and human systems and supporting decision-making. A great deal of untapped potential in a sensitivity analysis needs to be realized for the mathematical modeling of socio-environmental and other social problems complicated by uncertainty. Shahri et al. [131] examined that uncertainty quantification is a crucial metric for evaluating the effectiveness of deep learning ensemble-based models and other artificial intelligence systems. However, the available computational resources are constrained by the capacity of uncertainty quantification to use existing AI-based approaches. Also, it necessitates adjustments to topology and optimization procedures in addition to repeated performances to keep track of model instability. Ahmad and Alghamdi [132] observed that the data gathered from an experimental program using statistical planning are used to suggest a step-by-step statistical technique to obtain the best proportioning of concrete mixtures. The usefulness of the suggested method for improving the design of a concrete mixture is demonstrated by taking a typical case in which trial mixes were considered in accordance with a full factorial experiment design. Both sensitivity analysis and uncertainty analysis are important tools for ensuring the reliability and accuracy of HPC design and assessment and for improving the performance of concrete in various applications.

Life cycle assessment of HPC

Life cycle assessment (LCA) is a comprehensive and systematic method used to evaluate the environmental impact of a product or system over its entire life cycle, from raw material extraction to disposal. The LCA of HPC involves quantifying the energy consumption and emissions associated with each stage of the concrete life cycle. This includes extracting and processing raw materials, transportation, concrete production, construction, demolition, and disposal or reuse.

Stengel and Schiebl [133] found that HPC can enable more sustainable buildings when compared to typical concrete or steel structures. The use of a large quantity of energy-intensive raw ingredients, such as Portland cement or mineral admixtures, is primarily responsible for the exceptional mechanical qualities of HPC. Very high strength allows for reductions in cross-sectional area and weight of constructions. Overall, the LCA of HPC is an important tool for promoting sustainable construction practices and reducing the environmental impact of concrete production and use. By understanding the environmental impact of HPC over its entire life cycle, decision-makers can make informed choices about the use of HPC in construction and work towards a more sustainable future. Xing et al. [134] said that recycled aggregate concrete is anticipated to be a sustainable alternative to virgin aggregate concrete in structural use. Although life cycle assessment can address environmental challenges for consuming virgin aggregate and developing waste, relatively few studies have attempted to quantify these impacts.

Here's an overview of how LCA can be applied to HPC:

i. Raw materials extraction and production: The LCA of HPC would consider the environmental impacts associated with the extraction and processing of raw materials, such as cement, aggregates, and admixtures, used in HPC production. This includes energy consumption, greenhouse gas emissions, water use, and other environmental impacts associated with mining, transportation, and processing of raw materials.
ii. Manufacturing and production: The production of HPC involves batching, mixing, transportation, and placement of concrete, which requires energy, water, and other resources. The LCA of HPC would assess the environmental impacts associated with these processes, including energy consumption, greenhouse gas emissions, water use, waste generation, and emissions from construction equipment.
iii. Use phase: The use phase of HPC typically involves its service life as part of a structure or infrastructure. The LCA of HPC would consider the environmental impacts associated with the performance of HPC in terms of its durability, maintenance requirements, and energy efficiency. This may also include considering the impact of HPC on the overall energy consumption and environmental performance of the structure or infrastructure it is used in.
iv. End-of-life and disposal: The LCA of HPC would also consider the environmental impacts associated with the end-of-life phase, including potential disposal or recycling of HPC after its service life. This may involve considering the impacts associated with demolition, waste disposal, and potential recycling or reuse of HPC materials.
v. Comparison with alternatives: LCA can also be used to compare the environmental performance of HPC with alternative materials or technologies, such as conventional concrete or other construction materials. This can help identify the environmental benefits or drawbacks of using HPC compared to other options.
vi. Interpretation and decision-making: The results of the LCA of HPC can provide valuable information for decision-making and informing sustainable design and construction practices. The findings can help identify

areas where environmental improvements can be made in the production, use, and end-of-life phases of HPC, and guide efforts toward more sustainable practices, such as using recycled materials, optimizing energy use, reducing greenhouse gas emissions, and minimizing waste generation.

Summary

For the last few decades, HPC has been gaining interest worldwide day by day with applications ranging from bridges, building components, architectural characteristics, rehabilitation, repair, off-shore structures, vertical components such as utility towers and windmills towers to gas & oil industry applications and hydraulic structures. However, some restrictions limit HPC usage, and there is a lack of design codes and a limited understanding of the production technology and materials. Higher initial costs restrict the execution of this spectacular product. The government and private sectors should be growing their attention and enthusiasm for more efforts towards using this favorable and innovative concrete. This study outlines significant literature and provides some critical views on HPC with updated information on its growth and utilization. Based on the observations from the assorted literature, the following are summarized.

- The addition of fly ash (FA) and silica fume (SF) in high-performance concrete increases the demand for a superplasticizer for workable concrete. It occurs because the FA and SF have high specific surface areas.
- The ground granulated furnace slag (GGBS) mixed concrete gives better strength than the fly ash (FA) mixed concrete for similar conditions.
- The glass-fiber-reinforced HPC mixture containing FA and SF prevents the attack of acids better than the traditional concrete at every age of exposure to acid.
- The water absorption decreases by about 4.5% after replacing the cement with a 30% amount of GGBS. Also, the water absorption reduces by about 33.5% after replacing the fine aggregate with 100% copper slag.
- The HPC mix containing SF of 15% and natural pozzolana of 15% (by weight of cement) has been shown to have maximum safety against the sulfate attack. The study was conducted on immersed concrete specimens in sulfate solution and seawater for one year.
- The use of admixture is beneficial in increasing the density of the mix, which improves the compaction to prevent the penetration of any foreign agents within the mix.
- The concrete mix containing only silica fume has more strength than the concrete containing silica fume with fly ash when the water-binder ratio is within 0.25 to 0.35.
- The maximum compressive strength of HPC was found when the silica fume is in the ranges from 10 to 20%; however, it affects the economy.
- SF and FA are the waste materials of industries and are harmful to the environment. They pollute the environment badly if dumped. Reusing these as mineral admixtures for improving the concrete gives an additional advantage.
- Super-plasticizers are vital ingredients to keep the concrete workable and enhance its performance.
- For the mix blending with GGBS and FA, the compressive strength is less at an early age, but the gain is high at 28 days.
- Shrinkage is a potential concern in High-performance concrete (HPC); it can be effectively managed through proper mix design, the use of shrinkage-compensating admixtures, curing methods, and maintenance practices.
- HPC with low chloride permeability can provide improved durability performance in chloride-containing environments, leading to longer service life, reduced maintenance costs, and sustainability benefits.
- The application of high-performance concrete (HPC) involves careful selection of materials, precise mix design, quality control measures, and appropriate curing methods, all of which greatly impact its strength and durability characteristics.
- Proper application of HPC can result in a more durable and stronger concrete that is suitable for a wide range of demanding structural and infrastructure applications.
- The application of Life Cycle Assessment (LCA) to High-performance concrete (HPC) can provide a comprehensive understanding of the environmental impacts associated with HPC throughout its entire life cycle.

Future scope

HPC is a rapidly evolving field; new developments and advancements are constantly being made. In the early days, strength was the primary criterion in selecting concrete, but nowadays, durability plays a vital role in choosing concrete grades. HPC utilization is increasing day by day, but there are no specific Indian standards for the design mix of HPC. More experimental investigations need to be carried out on multi-blend concretes to achieve better strength and good durability properties. Some of the areas of focus for the future scope of HPC include:

i. Durability and Sustainability: HPC is required to be designed to improve its durability and sustainability, and future developments should focus on improving the long-term performance of HPC, particularly in harsh environments and under extreme conditions.

ii. Low Carbon Footprint: As the demand for sustainable construction practices increases, the focus of HPC development should shift towards reducing the carbon footprint of concrete production and use. This will involve reducing energy consumption and emissions associated with concrete production, as well as developing low-carbon concrete alternatives.
iii. Smart Concrete: The integration of smart technology into HPC is an area of growing interest, and future developments in this area should focus on incorporating sensors, actuators, and other advanced technologies into HPC to enable real-time monitoring and control of concrete structures.
iv. Recyclability: The increasing demand for more sustainable construction practices has led to a focus on developing recyclable and environmentally friendly HPC. This will involve using recycled materials in HPC production and developing methods for reclaiming and reusing HPC at the end of its life cycle.

Overall, the future of HPC is focused on improving the sustainability and performance of concrete while reducing its environmental impact. New developments in HPC will continue to drive innovation in the construction industry and contribute to a more sustainable future.

Declarations

Conflict of 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.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors

Informed consent In this study, the authors tried to elaborate on the use of supplementary cementitious materials as the replacement for cement and it is a systematic study on blended cement. This is the original and unpublished work.

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