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Research Article

A Critical Analysis Of The Development Of Strength In High-Performance Concrete: A Comprehensive Review

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ABSTRACT

Strength is an important characteristic of high performance concrete (HPC). The article explains how the water-to-binder (w/b) ratio, curing procedure, superabsorbent polymer (SAP), expansion-promoting additive (EPA), shrinkage-reducing additive (SRA), and supplemental cementitious materials (SCMs) affect the durability of high-performance concrete (HPC). Fly ash tends to reduce early age strength, however, this can be compensated by mixing it with nano-silica or other admixtures, as long as adequate levels of SCMs are present in the mix. The strength is maximised by reducing the aggregate size while increasing the aggregate strength. Fibers frequently have little effect on compressive strength, however they usually improve flexural and splitting tensile values. Using specific SCMs, the negative impacts of high temperature curing on later age strength can be reduced. When the w/b ratio is reduced, both strength and autogenous shrinkage (AS) rise. Although SAP and SRA hybridisation, as well as appropriate management of excess SAP-added water, have the potential to increase strength, additional study is needed.

Keywords: *High performance concrete; Natural admixtures; Steel slag; Strength properties; Durability.*

Introduction

Cement-based compounds are essentially quasi-brittle materials. Typically, they have limited ability to withstand strain, low resistance to cracking, low tensile strength, and poor energy absorption, which limits their potential applications (Alrekabi et al. 2017). Supplementary cementitious materials (SCMs) are powders that contain calcium, aluminium, and silicon compounds. They are used to partially replace clinker in cement or to partially substitute Portland cement in concrete (Mu et al. 2024). In order to control the progression of cracks and large-scale damage, several methods of applying Supplementary Cementitious Materials (SCMs) have been employed in Cement Based Composite Materials (CBCM). It has been suggested that the growth of nanoscale fractures can be prevented from expanding to the micro-level by using SCMs (Chang et al. 2020). Traditional methods for enhancing the strength and longevity of cement matrix involve the use of reinforcing materials, chemical additives, mineral admixtures, and controlling the water to binder ratio. The fundamental characteristics of CBCM are its variational complexity and nature. The link between various sizes of materials in concrete-based composites is that nanomaterials have the capacity to transform the processing of calcium silicate hydrate (C-S-H) from the microscale to the nanoscale, from level I to level II. Thus, nanomaterials play a crucial role in connecting particles at the level II and level III scales. Through the evaluation of nanotechnology in materials, a wide range of nanomaterials (NMs) have been created and employed in concrete structures. These include silica fume, nano-silica, nano-alumina, nano-clay, calcium carbonate, nanotube, nanofiber, graphene, and others (Taghipoor and Sadeghian 2022) (Djama et al. 2019). Evidence suggests that the strength of the cement is influenced by the adhesive properties and large surface area of the nano-sized C-S-H.

Supplementary cementitious materials (SCMs) such as silica fume, metakaolin, fly ash, and ground granulated blast-furnace slag are widely used in concrete binders worldwide, particularly in the manufacture of high-strength concrete (Kakemi and Hannant 1995). The components can enhance the performance of concrete by serving as filler and inducing a pozzolanic reaction. Many of the materials used as supplementary cementitious materials (SCMs) are industrial byproducts from other industries and therefore are readily abundant. Therefore, SCMs have become indispensable in reducing carbon dioxide (CO_2) emissions from concrete manufacturing (Alghamdi et al. 2024). Furthermore, the use of these substances as mineral admixtures for partially replacing cement can aid in the preservation of non-renewable resources employed in cement production and promote the development of more sustainable concrete construction (Wang and Wang 2015). The properties of concrete were altered by introducing different supplementary cementitious materials (SCMs) at both the initial and solidified stages. For example, when high-strength concrete (HSC) is treated with a regular amount of super-plasticizer and a comparable ratio of water to binder, supplementary cementitious materials (SCMs) might cause a delay in the setting periods of the concrete (Yang et al. 2020). In general, fly ash enhances the workability of concrete, however, it may reduce the strength of the concrete at an early stage. The use of partial cement replacement materials or mineral additives as partial cement replacement materials might result in diverse effects on the properties of concrete, which are contingent upon the specific components involved. This is because they have different mineralogical and chemical compositions, as well as varying particle characteristics, which control their ability to pack, their water requirements, and their reactivity when used in concrete (Han et al. 2016) (Winslow and Liu 1990). Researchers have consistently focused on the influence of fiber reinforcement on the properties of hardened concrete. Concurrently, many publications discussed hybrid fibers, synthetic structural fibers, and fiber reinforcement using pozzolanic chemicals. These research activities are further exemplified. The study examined the effects of different hybrid fiber combinations, specifically steel-glass, steel-polyester, and steel-polypropylene, on concrete. In addition, fibers often assist in the energy absorption system by a bridging function. Nevertheless, the presence of non-metallic fibers resulted in a deceleration of micro-cracking. Ultimately, the inclusion of fiber enhanced the load-deflection curve's first section before reaching its highest point, leading to an augmentation in the ability to resist bending and an enhancement in the section after reaching the highest point, resulting in improved durability.

1. Why it is necessary?

Researchers are currently promoting the utilisation of fiber-reinforced cementitious composites (FRCC) in various concrete structures, including airfield runways, refractory structures, bridge beams, tunnel lining structures, anti-explosion structures, and more. This is due to the exceptional mechanical properties and long lifespan of FRCC (Han et al. 2016). It is crucial to prioritise the safety analysis of structures constructed using FRCC when employing it in intervention engineering applications, especially in the context of advancing High-performance Cementitious Composites (HSCC) and High-Performance Concrete (HPC) (Huang et al. 2015). Fractures in FRCC can lead to failures, which may be caused by random inherent faults. These defects are greatly influenced by the multiphase features of the FRCC. Multiple experiments have been conducted to assess the numerous characteristics of the FRCC, analyze issues such as fracture stability and mechanical qualities, and establish the safety of FRCC constructions (Gao et al. 2024). The current literature on the practical research of Quaternary binder mixes in FRCC is minimal. Various research studies have been conducted in the literature about the substitution of binary and ternary materials in traditional concrete. This article provides a comprehensive examination of the testing procedures employed to study the characteristics of Fiber Reinforced Cementitious Composites (FRCC) in the presence of Supplementary Cementitious Materials (SCMs). This article seeks to offer a comprehensive perspective on the substitute materials employed in Fiber Reinforced Cementitious Composites (FRCC) and to establish a comprehension and evaluation of the FRCC when various supplemental materials are utilised, in addition to the derived advantages.

2. Type of materials used

Microfiber or Nanofiber
The fracturing of these threads starts at the microfiber or nanometre scale. The fracture failure features of microfibers or nanofibers are attributed to the accumulation of stress within the vicinity of micro-cracks. Moreover, the multi-walled carbon nanotube exhibits exceptional reinforcement and toughening abilities because of its unique chemical characteristics, mechanical capabilities, and high aspect ratio. Thus, the incorporation of a multi-walled carbon nanotube can greatly enhance the fracture characteristics (Caggiano et al. 2016).

Macro Fiber
Steel fibers are commonly and widely employed in scientific research and engineering to enhance the properties of cement-based products (Feng et al. 2018). The fracture characteristics of FRCC are contingent upon the mechanical properties of the steel fibers. The fracture energy of steel fibers is directly influenced by

their tensile strength, which is the main determining factor. When the water-to-cement ratio remains constant and steel fiber-reinforced cement is added, the steel fibers with sufficient stiffness result in increased fracture energy. Diverse varieties of steel fibers in Figure 1 and Table 1 provide information about the characteristics and various forms of steel fibers. Additionally, the fracture properties of Fiber-reinforced cementitious composites are dependent on the specific kinds of steel fiber employed. Steel fiber is highly effective in enhancing fracture toughness and fracture energy. Nevertheless, the progress and improvement of the fracture zone phenomenon are equally crucial for the structural behaviour of concrete. To regulate the growth of the fracture process zone, steel fibers are included in the cement mortar, therefore inhibiting crack propagation.

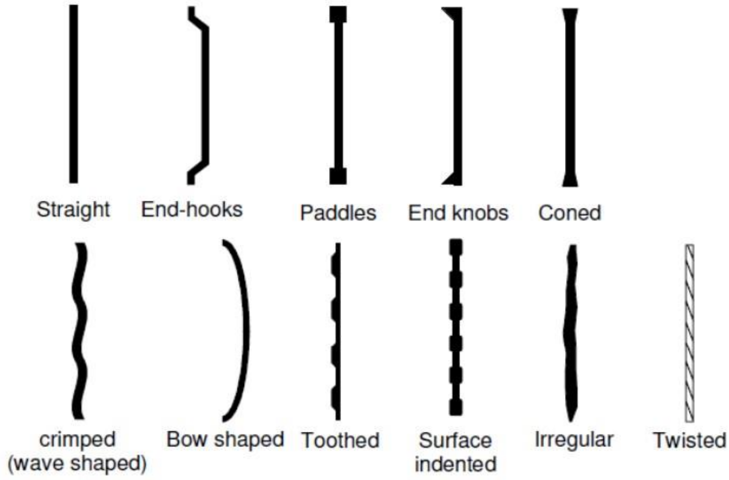

Figure 1: Variations in steel fibers

The usage of steel fiber in chemically hostile conditions leads to a durability concern, which is an undesirable consequence related to magnetic or electric fields (Xu et al. 2019). Hence, synthetic fibers, which possess superior electromagnetic interference and chemical stability in comparison to steel fibers, are being increasingly utilised as alternative reinforcing materials. Polypropylene, polyvinyl alcohol, and polyolefin fibers are often utilised. The use of polyolefin fiber in self-compacting concrete resulted in a significant increase in energy absorption due to the enhanced ductile properties. Lower modulus polypropylene fibers are commonly used to reduce concrete shrinkage and prevent flammable spalling. The mechanical and geometrical features of PP fiber have a vital role in the ductility and fracture qualities of concrete (Zhang et al. 2024). The use of high-ductility polypropylene fibers in concrete with low and intermediate strength resulted in a significant increase in energy absorption due to the pullout mechanism of the fibers. Additionally, the increased energy percentage can be attributed to the use of high-strength concrete that is reinforced with more robust and thicker polypropylene fibers, resulting from the rupture of these fibers. Polypropylene fiber is employed to mitigate the significant boundary impact.

In order to strengthen the cement foundation, synthetic and steel fibers are included together with inorganic mineral fibers such as carbon, basalt, brucite, and glass fibers. Carbon fiber exhibited superior fracture energy, fracture toughness, and load-bearing capability. Basalt fiber has a high elastic modulus, great strength, and long-lasting resilience. The incorporation of glass fiber and basalt fiber in concrete enhances its fracture energy, whereas the absence of these fibers results in reduced fracture energy. Hence, basalt fiber surpasses glass fiber in enhancing the fracture characteristics of concrete. The incorporation of brucite fiber into cement-based materials resulted in favourable fracture properties (Zhang et al. 2024). Macro fibers, in contrast to microfibers or nanofibers, have a vast array of varieties and sources. Various macro fibers have been employed in technical applications. Steel fibers are utilised in pavements, polyvinyl alcohol fibers are employed in cementitious composites, and basalt fibers are utilised for road reinforcement. Microfibers have limited uses, but they are particularly valued in laboratory settings because of their higher cost in large-scale manufacture and assembly.

Table 1: Different types of fibers with their results

Material type	Concrete type	Outcomes
SBR & Steel fiber	Conventional	A 15% increase in compressive strength has been observed after using 15% of SBR. Gap: The use of PP can enhance the binding properties as well
SBR, Steel fiber & PP	UHPC with CFRP bars	Ultimate bond improved by 45% and 87% when 1% of either PP or steel fiber was added.
SBR & Polymers	Fly-ash based UHPC	The usage of rubber increases the tensile strength by 50%
PP & steel fiber	HPC	With increasing temperature, there is a decrease in compressive strength of different mixes. Usage of PP by 2% shows significant benefits in increasing compressive strength but workability declines.
PP & Glass	UHPC	The result indicates that 2% fiber content in UHPC provides better mechanical properties.

fiber		The toughness index increases 3.8 times more than conventional.

Hybrid fibers
The primary objective of using hybrid fiber is to provide exceptional performance within a certain spectrum, encompassing cement mortar, cement paste, concrete, and calcium silicate hydrate gel. Hybrid fibers of varying diameters exhibit different levels of reinforcement within different ranges. More precisely, the uniform distribution of short fibers regulates the formation of microcracks, whereas long fibers effectively link these microcracks together. The use of both microfiber and macrofiber can enhance the strength and durability of cellular lightweight concrete, particularly in terms of fracture resistance (Taghipoor and Sadeghian 2022). In addition, the presence of short fibers can reduce the porosity of the material, whereas macrofibers can enhance the strength and durability of the cement matrix. Short macrofibers function as little shovels, aiding in the reduction of porosity and facilitating the thorough mixing of fresh concrete during the casting process. The concrete with hybrid fiber reinforcement achieved the highest energy percentage value due to the combined reinforcing effects of the two kinds of fiber. In addition to enhancing the cement matrix and increasing resistance to cracking, the interaction of hybrid fibers also enhances the behaviour of fracture characteristics (Teng et al. 2018a). Another form of hybridisation involves combining fibers with differing moduli. The addition of polypropylene fiber to steel fiber-supported concrete-based composites enhances the energy absorption capacity due to the synergistic effect of both types of fibers. Fracture toughness was shown to have an interaction impact when polypropylene fiber was combined with large steel fiber with a hooked end during low deflection, as observed in a previous study. The interaction effect becomes less advantageous when there is an increase in the deflection. The study found that combining polypropylene fibers, which have a low modulus, with basalt fibers, which have a high modulus, effectively reduced fracture widths and improved the energy absorption capacity of high-performance concrete (Swolfs et al. 2014).

Fiber aspect ratio
When analysing the qualities of fiber-reinforced cementitious composites, it is important to consider the fiber aspect ratio, which is expressed as lf/df, representing the ratio of the fiber's length to its diameter. Typically, the uneven distribution of fiber with a strong potential is noticed when the lf/df increases. Therefore, the range of 50 to 100 governs the value of lf/df for steel fiber. A high ratio of lf/df suggests a larger number of fixed fibers, which implies a bigger surface area for the fiber. The fracture energy with an L/d ratio of 80 was reported to be the highest, whereas the fracture energy for lesser L/d ratios ranged from 55 to 65 (Sarasini et al. 2018).

Replacement Materials
Reactive powders, such as GGBS, silica fume, and fly ash, can be used as substitutes for regular Portland cement in high-performance FRC. The reactive powders depicted in Figure 6 are characterised by their tiny size and can produce concrete with a compact microstructure. Reactive particles are used to improve the mechanical characteristics of concrete at normal temperatures. For instance, the addition of 20% fly ash to the concrete results in an outstanding performance at room temperature (Qian and Stroeven 2000). The concrete achieves its highest compressive strength when exposed to a temperature of 800 °C. Moreover, the use of silica fume can enhance the secondary hydration process. This promotes the development of a more compact microstructure. Concrete achieves its highest compressive strength when 20% of silica fume is included. The optimal performance of silica fume may be achieved within the temperature range of 200 °C to 300 °C. The use of GGBFS can reduce the porosity of the concrete and enhance its strength. While reactive powder generally enhances the performance of fiber-reinforced concrete under normal room temperature conditions, it does not consistently provide the same benefits for fiber-reinforced concrete at elevated temperatures. For example, the addition of silica smoke or metakaolin to fiber-reinforced concrete at room temperature results in increased compressive strength compared to cement without any substitution element. Nevertheless, at a temperature of 800 °C, the concrete exhibits exceptional compressive strength when substituted with other materials. The very compact microstructures of silica fume and metakaolin are the reason for this (Swathi and Asadi 2022).

Effect of special binders
Fly ash (FA) and calcium carbide are two types of industrial byproducts that are utilised as binders with minimal carbon dioxide (CO_2) emissions. The ground calcium carbide residue (CR) was mixed with either Ground Fly ash (GF) or original fly ash (OF) at a weight ratio of 30:70. Additionally, it served as a means to secure concrete that did not include Portland cement. The mechanical characteristics of the solidified concrete generated with CR-GF and CR-OF blends were found to be similar to those of regular Portland cement concrete. The study examined the significance and limitations of enhancing cementless concrete by utilising Hwangtoh-based alkali-activated concrete blends (Teng et al. 2018b). In order to produce a binder without cement, the researchers mixed a specific form of kaolin called hwangtoh with inorganic components, specifically calcium hydroxide. The quantity of fines and the ratio of water to binder were the two primary factors examined. The splitting tensile strength, compressive strength, stress-strain relationship, rupture and elasticity moduli, and bond blockage were estimated. The water-to-binder ratio had a significant influence on

the mechanical properties of concrete made using hwangtoh, whereas the percentage of fine aggregate to total aggregate had a lesser effect (Habel et al. 2006).

Aggregates

Aggregate is a granular substance that plays a vital role in the composition of concrete. There are two forms of conventional aggregate: siliceous aggregate and carbonate aggregate. When exposed to extreme temperatures, they exhibit contrasting behaviour (Caggiano et al. 2016). Carbonate aggregates typically possess a smaller pore structure in comparison to siliceous aggregates. According to reports, the highest specific heat of siliceous aggregates was found to be between 150°C and 400°C, whereas for carbonate aggregates it was 500°C. At temperatures over 600°C, dolomite has the potential to dissociate, resulting in the disintegration of carbonates and the subsequent production of carbon dioxide gas. Carbonate aggregate concrete exhibits higher heat absorption capacity than siliceous aggregate concrete, resulting in enhanced fire resistance (Yahyaee and Elize 2024). In addition to traditional aggregate, there has been increased focus on recycled aggregates in recent years due to their ability to significantly reduce environmental pollution. During the exploratory evaluation of SFRC (Steel Fiber Reinforced Concrete) with recycled concrete aggregates, which includes both fine and coarse aggregates, the residual compressive strength was found to be 85% after subjecting it to a high temperature of 200°C. However, the compressive strength decreased to 59% when exposed to 400°C and further decreased to 39% when exposed to 600°C. The residual compressive strength of Steel Fiber Reinforced Concrete (SFRC) exhibited a little drop when including recycled concrete aggregates and crumb rubber, as reported in reference.

Furthermore, leftover glass aggregate is included in concrete to enhance its fire resistance. Waste glass aggregate concrete has comparable compressive strength at both high and normal temperatures. Nevertheless, subjecting scrap glass to temperatures over 600°C enables it to effectively occupy the empty spaces and microscopic fractures inside concrete. During the trial evaluation, the addition of 10% waste glass at a temperature of 700°C resulted in a 100% increase in the compressive strength of the material (Guo et al. 2024).

Effect of natural aggregates

The usage of limestone as aggregates in the building industry has been increasing due to its several benefits. Some of these benefits include excellent durability, reduced drying shrinkage, and minimal risk of alkali-silica reaction in concrete (Banyhussan et al. 2016). This study examines the use and shared characteristics of limestone aggregate in Japan and the USA. Tests were conducted on different water/cement (w/c) ratios using varied sand and fine limestone proportions. The selected water-to-cement ratios were 40%, 50%, and 60%, whereas the limestone substitutes were 0%, 30%, 50%, and 100% (Megahed et al. 2018). To establish a correlation between drying shrinkage and water trapped in the exterior gaps of sand and fine limestone, the porosity and water absorption of these materials were assessed. The results demonstrated an increase in the modulus of elasticity, flexural strength, and compressive strength as the amount of fine limestone in the mixture increased. Significant improvements are noticed in the drying shrinkage, which decreases significantly as the amount of fine limestone increases. An analysis was conducted on the effect of several types of aggregate (limestone, basalt, sandstone, gabbro, and quartzite) on the abrasion resistance and toughness of high-strength silica fume concrete (Gu et al. 2024). Gabbro concrete had the highest flexural strength, compressive strength, tensile strength, and abrasion resistance, whereas sandstone displayed the lowest values in these properties. The compressive strengths of three-month concrete specimens formed from sandstone, limestone, and basalt were the same as the uniaxial compressive strengths of their respective component rocks. However, the concrete prepared with quartzite and gabbro aggregate exhibited lower compressive strength when compared to the uniaxial compressive strength of the rocks used as aggregate. The researchers examined the correlation between the methylene standards of concrete specimens created with aggregates from different extractions and the ultrasonic pulse velocity, resistance to surface abrasion, and compressive strength. In order to determine the characteristics of the micro-fine material that can pass through a sieve with a mesh size of 0.063 mm, experiments were carried out. The methylene value test demonstrates that clay substance has an impact on the solid qualities. However, the microfine material rate is not directly related to the clay matter.

3. Impact of w/c or binder ratio

The water-cement (w/c) and water-binder (w/b) ratios have a significant physical significance. They determine the amount of water relative to the amount of cement or binder used in a mixture. Understanding the nature of Portland cement and how it undergoes hydration is also crucial in this context. The w/c (water-to-cement) and w/b (water-to-binder) ratios are closely correlated with the spacing between cementitious particles in a cement paste at the onset of the hydration process. These ratios have a direct influence on the final porosity, density, and mechanical characteristics of concrete. The concrete's strength, durability, and sustainability increase as these ratios decrease. Superplasticizers enable the manufacturing of concrete with reduced water content while maintaining its workability, leading to significant advancements in concrete performance. Within this particular type of concrete, there is an insufficient amount of water for full hydration. As a result, the compressive strength of the concrete continues to rise when the water-to-cement or water-to-binder ratio drops (Cwirzen et al. 2009).

4. Impact of different fibers on compressive strength

Similar to regular concrete, the compressive strength of High-Strength Concrete (HSC) is a crucial and frequently evaluated characteristic. In order to prevent explosive failure, it is necessary to include fibers. When comparing HSC with fibers to conventional concrete, there is not a significant difference in compressive behaviour. However, the main improvement lies in the increased stiffness and compressive strength. The compressive strength is influenced by factors such as the mix percentage, fiber content, component materials, and curing conditions (Yang et al. 2023). The addition of fibers seems to have little impact on the compressive strength of cement. However, this conclusion only differentiates between high-strength concrete (HSC) that is reinforced with fibers and HSC that is not reinforced, and it is not influenced by the percentage of fibers present. Increasing the fiber content to 3% seems to mostly help small cubes measuring 40-50 mm. The compressive strength decreases as the values increase, eventually reaching a level similar to that of the High-Strength Concrete (HSC) without fibers. The presence of fiber clusters and reduced workability, resulting in the entrapment of air, may explain the observed decline in compressive strength (Zhang et al. 2024). However, it is still uncertain if the reported variations in results may be attributed to arguments regarding the shape of the test samples rather than the actual effects of the fibers. According to research, cylinders are believed to represent a more robust distribution of stress in one direction, as opposed to cubes. The internal shear stress significantly affects the compressive failure of cubes, particularly at the corners and when the height-to-cross-section ratio is less. However, a limited amount of data is displayed. Different factors, including the materials used, the amounts of the mixture, and the way the curing process is carried out, might lead to a greater range of test results compared to variations in the shape of the test specimens (Yoo et al. 2013). According to the authors of this study report, there are indications that the form of the test specimen may potentially influence the findings of the inquiry.
The experimental findings demonstrated that including supplemental cementitious elements, such as FA, SF, GGBS, and MK, in the cement impacts the characteristics of concrete. According to the test findings, the use of pozzolanic elements in quaternary concrete enhances its compressive strength. This gain in strength suggests that the effectiveness of pozzolans is more pronounced when the water/binder ratio is low.

5. Impact of fibers on direct tensile strength

The utilisation of deformed fibers has resulted in a significant enhancement in the direct tensile strength of concrete in comparison to straight fibers. A significant improvement in the direct tensile strength when twisted fibers were utilised. Additionally, some minor differences were noted between two types of hooked end fibers (l=62mm and l=30mm) for the 1 vol-%, as well as for the big straight fibers with (l=30mm). The micro-hooked end fibers (l=13) exhibit higher tensile strength compared to the macro-hooked end fibers (l=30). The decreased amount of fiber and the decreased frictional adhesion have explained the diminished effectiveness of the hooked end fibers. Despite the greater pullout capability of the twisted fibers, some investigations have found that using deformed fibers instead of straight ones leads to a reduced impact of only 15%. In comparison to the straight microfibers (with a length of 13), (Yoo et al. 2014) observed a significant decrease in the tensile strength of two types of macro twisted fibers (15%) and macro hooked end fibers (>40%). The justification for this lies in the significant bond strength and the congestion of fibers that impact the matrix. In addition to the 20mm and 9mm fibers, the 13 mm fibers have been shown to have higher tensile strength.

Hybrid fibers combinations
The hybrid fiber is composed of a mixture of long and short fibers (Park et al. 2012). This has the potential to decrease the quantity of fiber while maintaining its efficacy. The evaluated research examined the method of combining microfibers with long and hooked-end fibers (Kakemi and Hannant 1995) (Chavhan et al. 2023). Only a small number of researchers have investigated the process of combining different straight fibers. The influence of incorporating hybrid combinations of fibers on compressive and flexural tensile strength may be observed. Distorted macro fibers have the disadvantage of inducing destructive split fractures in the matrix, whereas straight microfibers have limited pullout strength.

6. Different Properties of FRC

Elastic modulus
The elasticity modulus of concrete is mostly determined by the volume of the material and the characteristics of the transitional area, in contrast to homogeneous materials. The elastic modulus of FRC can significantly

decrease as a result of changes in the microstructures and the degradation of the chemical bond at elevated temperatures. Adding fibers to fiber-reinforced concrete at room temperature will very slightly affect its elasticity modulus. The residual elastic modulus of the fiber-reinforced concrete rises due to the enhanced microstructure resulting from the heat treatment (Yong et al. 2022). A study conducted by (Alghamdi et al. 2024) found that the use of polypropylene (PP) fibers in fiber-reinforced concrete might delay the loss of modulus by reducing thermal damage caused by the melting of the PP fibers. The experiment demonstrated that the relative elasticity modulus of the group with PP fibers at 400°C was 22% higher compared to the group without PP fibers. It is argued that the presence of polypropylene fiber has a minor impact on the residual modulus of elasticity of fiber-reinforced concrete. The dosage of fibers and the kind of fibers used have a low influence on the residual modulus of elasticity, particularly at temperatures over 600°C, the addition of steel fibers can increase the modulus of fiber-reinforced concrete (FRC) to some extent when it is exposed to a high temperature of 900°C. Conversely, the modulus does not incorporate polypropylene fiber. The addition of 1% stainless steel fibers was shown to significantly improve the elasticity of fiber-reinforced concrete (FRC) at a temperature of 800°C, surpassing the performance of FRC reinforced with hybrid polypropylene fibers.

Toughness
The toughness of cementitious materials is a crucial attribute that determines the material's capacity to absorb energy. Concrete toughness is commonly defined as the area enclosed by the stress-strain curve. The hardness of the fiber-reinforced composite (FRC) typically decreases as temperature rises, mostly owing to the loss of compressive force. Incorporating stainless-steel fibers enhances the hardness of the material. Additionally, at room temperature, it exerts a favourable influence on FRC, whereas the impact of PP fibers is insignificant. The toughness of SFRC has an upward trend from room temperature to 200°C when using FRC containing 1% stainless steel and recycled composite. However, it starts to decrease after 200°C. An increase in temperature may result in a greater peak pressure, perhaps leading to an upward trend before reaching 200°C. However, a contrasting pattern is observed when the same percentage mixture is used (Zhi et al. 2024), as the reduced capacity to withstand heat can be linked to the use of recycled cement aggregate in the experiment (Bharathiraja et al. 2020).

Permeability
Permeability is a prominent characteristic of FRC. In general, a high level of permeability is an indication of a high level of porosity, which in turn affects the strength of the material (Toutanji et al. 1998a). Furthermore, a greater permeability facilitates the easy penetration of chloride ions into the concrete composite, hence diminishing the durability of FRC. Insufficient permeability can lead to the occurrence of FRC spalling in high-temperature circumstances. Typically, the variations in temperature and the makeup of substances are intricately linked to the permeability. When the Cementous material was exposed to high temperatures, the pore structure was found to be eroded, resulting in a loss in resistance and an increase in permeability (Huang et al. 2022).

Spalling resistance
During FRC, spallings would form because of extreme conditions such as a sudden rise in temperature, strong heat, a greater presence of chloride ions (Toutanji et al. 1998b), and explosive shocks. Typically, spalling does not occur at elevated temperatures in regular concrete. High-strength fiber-reinforced concrete (FRC) often has a lower water-to-binder ratio (w/b) compared to ordinary concrete, resulting in reduced porosity. This can make it more difficult for water vapour to escape from the concrete, increasing the likelihood of cracking (Huang et al. 2022). Thus, thermal spalling is commonly used as a crucial parameter to study the fire resistance of FRC and to assess the behaviour of Fiber Reinforced Concrete at elevated temperatures. The internal part would experience elevated temperatures, leading to an expedited deterioration of the concrete due to heat-induced failure occurring on the exterior surface. The thermal expansion of FRC (fiber-reinforced composites) when heated is a primary cause of thermal spills with FRC. Due to its low thermal conductivity, the cemented material is susceptible to thermal stress and deterioration when there is a significant temperature difference between the heating surface and the cooling centre. Furthermore, the elevated pore pressure within the FRC also plays a substantial role in causing spill damage. At high temperatures, the evaporation of bound water leads to the production of water vapour. Due to the typically thick FRC microstructure, it is challenging to completely release the vapour pressure. This can significantly increase the pore pressure inside the microstructure and lead to FRC blasting.

Air permeability
An analysis of the different permutations between 28 and 56 days reveals a decrease in Ap, which is thought to be caused by the ongoing hydration of the cementitious components. Given that nearly all of the blends exhibited significant improvements, determining which kind of cementitious mix resulted in the greatest reduction in air permeability was challenging. After 28 days, the addition of 7.5% SF resulted in a moderate increase in air penetrability, but the inclusion of 15% SF caused a significant reduction in Ap. The air

permeability of these blends increased as the SF concentration increased, yet all of the 28-day values were greater than the 56-day values. The addition of SF is anticipated to have an impact on the microstructure due to its ability to fill voids and enhance pozzolanic reactivity. This requires more advancement in the Ap at both 28 and 56 days. For instance, The observed increase in air permeability with increasing SF concentration at 56 days is a surprising discovery that justifies further investigation. Two variables might account for this diversity. Initially, if the concrete has a high density, the Autoclam's sensitivity may not be sufficient to differentiate affects on the Ap at 56 days. Furthermore, before doing permeation tests, the process of preconditioning might have resulted in moisture gradients inside the material, potentially leading to significant microstructural alterations. Both of these components may have contributed to the 56-day patterns, either alone or in combination (Yusof et al. 2013).

Bulk resistivity

The resistivity of all the binary and ternary combinations rose by a factor of 5 to 17 compared to the control mix. In SCM mixes, the pores exhibit regular irregularity as a result of the denser microstructure. As mentioned earlier, the incorporation of Supplementary Cementitious Materials (SCMs) can have two outcomes: increased compactness of the microstructure and the formation of Calcium Silicate Hydrate (CSH) through a pozzolanic reaction. Both of these components can contribute to an increase in resistivity. The SCM mix SF15 had the highest resistivity, whereas the blend BS50 demonstrated the lowest resistivity. Based on previous studies, the addition of SF to FA and GGBS combinations increased their resistivity (Sarlin et al. 2014).

Chloride diffusion

A study revealed that the utilisation of a 7.5% SF (silica fume) resulted in a halving of the diffusion coefficient (De) as compared to a mixture consisting only of OPC (ordinary Portland cement). The decrease in De was only 5% when the concentration of SF was raised from 7.5% to 15%. Consequently, it may be contended that increasing the SF concentration above 7.5% does not yield any substantial advantage. The influence of GGBS on De exhibited a similar trend to that of SF. When 50% GGBS was used, the value of De decreased by three times, however raising it to 65% did not result in a substantial increase in chloride diffusivity (Du et al. 2016). The most optimal outcomes were achieved by blending 7.5% SF with 50% BS. The most effective blend of Ground Granulated Blast Furnace Slag (GGBS) and Silica Fume (SF) to inhibit the diffusion of chloride ions in High Strength Concrete (HSC) was identified. The relationship between the bulk resistivity of concrete and its diffusivity was found to be inversely proportional. Adding supplementary cementitious materials (SCM) to Portland cement (PC) concrete increased the surface chloride content (Cs) of all the blends, as seen in a study (Mangat and Gurusamy 1987). The addition of these mineral additives leads to the formation of more calcium aluminate hydrates, which then react with chlorides to form Friedel's salts. The partial replacement of Portland cement (PC) with fly ash (FA) at both substitution levels, and with ground granulated blast furnace slag (GGBS) at a 50% substitution level, increased the Cs. The drop in the value of Cs in SF replacements can be attributed to the presence of smaller tricalcium aluminate phases in these mixes. The inclusion of SF in a binary mixture including FA or GGBS led to a decrease in Cs, maybe attributable to the same underlying cause as previously observed. The reduction in Cs is most noticeable in FA ternary blends using the lowest quantity of PC (Liu et al. 2019).

Conclusions:

The strength of high-performance concrete (HPC) is a critical characteristic. The paper examines the influence of many factors, such as the water-to-binder (w/b) ratio, curing technique, superabsorbent polymer (SAP), expansion-promoting additive (EPA), shrinkage-reducing additive (SRA), and supplemental cementitious materials (SCMs), on the long-lasting quality of high-performance concrete (HPC). Fly ash has a tendency to reduce the strength of concrete at an early stage. However, this effect may be counteracted by using nanosilica or other admixtures, provided that a sufficient number of supplementary cementitious materials (SCMs) are also added to the mixture. The strength is optimised by reducing the overall size of the aggregate and enhancing the strength of the aggregate. Fibers generally do not have a significant impact on compressive strength, but they frequently enhance the flexural and splitting tensile values. By employing certain Supplementary Cementitious Materials (SCMs), it is possible to reduce the negative impact of high-temperature curing on the strength of the material at a later stage. Reducing the water-to-binder ratio leads to an increase in strength, but it also results in a rise in autogenous shrinkage (AS). While the combination of SAP and SRA through hybridisation and the effective management of surplus water can enhance strength, further study is needed to fully understand and optimize these technologies. It is recognized that including an appropriate quantity of fiber in high-strength concrete is crucial as it enhances its durability and resilience. However, it is crucial that the fiber content is neither overly high nor excessively low since this might result in the formation of internal abnormalities. The addition of polypropylene fibers, together with high-strength steel fibers and varying amounts of MK, resulted in improved split tensile strength, compressive strength, and bond strength. The low elastic modulus of propylene fiber improves the compressive strength of concrete. Consequently, the frequency of cracks is greatly reduced. Steel fibers have a much greater elastic modulus, whereas polypropylene fibers have a noticeably lower elastic modulus. As a consequence, they synergistically perform well and lead to improved mechanical functionality.

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