CHAPTER 2 LITERATURE REVIEW

2.1 GENERAL

Concrete has widespread applications in different spheres of infrastructure, and sometimes ordinary concrete alone may not withstand certain adverse conditions due to its lesser longevity and lower strength. Therefore, chemical or mineral admixtures are applied to enhance the properties of the concrete. The properties of the concrete are affected differently by different admixtures [55].

Admixtures are components injected into the concrete mix during the mixing. They have many beneficial influences on concrete, including reduced water requirements, enhanced workability, controlled setting, accelerated hardening, improved strength, better durability, desired coloration, volume changes, etc. The pozzolanic mineral admixtures are finely divided materials used in cement mortar and concrete to achieve specific engineering properties. Using mineral admixtures in concrete serves the dual purpose of economic and environmental benefits, as almost all of them are derived as waste from various industries [26].

The latest trend is to utilize more mineral admixtures such as fly ash (FA), (GGBS), Micro Silica (MS) etc., as a direct replacement in the range of 5-70% by mass of total cementitious materials. In addition to reducing the use of cement, mineral admixtures also enhance the chemical, mechanical, and physical qualities [24][25]. The Concrete Admixture Handbook [26] describes that finely divided mineral admixture reduces the quantity of water required to achieve specific consistency of mortar or concrete; however, when the same is used in a large amount, water demand increases. In such cases, chemical additives like superplasticizers and air-entraining agents are used to maintain a particular consistency. The fine mineral admixtures do not lead to a denser granular packing of the cementitious matrix without SP [27].

The previous research on the effects of different mineral and chemical admixtures (natural and/or synthetic) on the mechanical and durability qualities of concrete has been examined in this chapter. Compared to aggregates, the behaviour of the hydrated cement paste has a far greater impact on the characteristics of concrete. Therefore, it is essential to understand how different mineral admixtures affect cement paste and mortars in order to comprehend how they affect the qualities of concrete. The primary goal of these earlier investigations was to enhance the characteristics of cement paste, mortar, and concrete. Understanding the outcomes of the current investigation will be greatly aided by the analysis of these mineral and chemical admixtures.

2.2 LITERATURE REVIEW ON SECONDARY CEMENTITIOUS MATERIALS (SCMs)

2.2.1 Fly Ash (FA)

FA, or pulverized fuel ash, is a byproduct of coal-fired power plants and is used as a mineral additive in cement and concrete. The features of FA are influenced by various factors, including the type of coal used, the burning conditions, the collection mechanism, etc. [56]. The use of FA as a pozzolanic ingredient and its reaction potentials were first recognized in early 1914; however, a substantial study on the use of FA in concrete was first published in 1937 in the United States [57][56]. In the earlier studies in the 1980s, it was reported that replacing concrete with FA can significantly improve the mechanical and durability properties of concrete [58] as FA can improve the microstructure of the paste [59]. Depending on the application, FA properties, specification limits, geographic location, and climate, FA has traditionally been incorporated in concrete at levels ranging from 15 to 25% by mass of the cementitious material component [60]. It was reported that, in some rare cases, concrete had been successfully placed incorporating up to 80% FA [61].

The FAs used in concrete are of two types class F and class C according to ASTM. The class F FA is a by-product of bituminous coal combustion. The iron, silica, and alumina content of class F FA is high, but the calcium content is low. It's a glassy substance that requires either cement or lime to activate. FA from sub-bituminous coal and lignite combustion is classified as class C. It contains more calcium than class F FA. Concrete containing class C FA develops strength much more quickly than concrete containing class F FA [56][61]. The use of FA in concrete is cost-effective, but it also changes the concrete properties in its fresh and hardened states, improving workability, strength, and drying shrinkage. Furthermore, the use of FA in concrete solves the storage and disposal problem of FA, an industrial by-product [62].

2.2.2 Effect of FA on Fresh Cement and Concrete

2.2.2.1 Consistency

Consistency of blended cement increases with FA replacement, resulting in higher water demand for the same consistency in comparison to the ordinary Portland cement (OPC), according to Dave et al. [63]. In this study, replacing 30% and 50% of OPC with FA resulted in a 1.6 and 3.1% increase in standard consistency, respectively, due to the improved fineness of the blended mix. Qafleshi et al. [64] reported a 2.6% increase in consistency with a 30% replacement of calcareous FA. A similar observation was made by Turgut et al. [65] in blended cement with the FA from the precipitator of the thermal station and with the hydrated FA as the FA replacements increased the water demand for the normal consistency. Kishan et al. [66] examined the consistency as per IS 4031–part

4 (1988) with 20% FA replacement with or without superplasticizer (SP). This study found that admixed paste consistency is higher than the OPC paste with or without SP. Further consistency of paste with SP was lower than without SP.

The experimental studies by Kizilkanat et al. [67], according to ASTM C187 standards [68] on mortar incorporated with class F FA, showed that up to 35% of FA replacement the blended cement paste's normal consistency remained the same as that of plain PC paste. Further, they found that the depth of penetration in FA paste was more than the PC paste because FA particles have spherical shapes which reduced the inter-particle frictional force and particles surface to volume ratio, resulting in lower water demand. Other studies also reported a drop in water demand as the FA level increased. Elmrabet et al. [69] found that the w/c ratio required for normal consistency reduced as FA concentration increased, ascribing to the glassy spherical particles found in FA.

2.2.2.2 Setting Time

The setting time of mineral-admixed pastes normally increases with the percentage of minerals added increases [70]; as the fineness of FA increases, the setting time of FA cement decreases. One of the earlier studies on high volume FA concrete (HVFAC) with FA ranging from 35 to 50% reported an increase in setting time with the increase in FA content. The study examined both C and F class FA and found that the initial setting time varied from 20 minutes to 260 minutes, while the final setting time varied from 60 minutes to 315 minutes, depending on the type and amount of FA. As a result of the high sulfate content on the surface of the class C FA particles, the setting time was longer than that for class F FA [71]. Dale et al. [72] also reported that class C FA admixed mixtures had a longer setting time than class F FA in HVFA mixtures. However, according to this study, adding 5% calcium hydroxide (CH) powder and 5 to 10% rapid set cement significantly reduced the delay in the setting time of HVFA mixtures. Both initial setting time and final setting time of concrete increased with an increase in the replacement level of class C FA from 10 to 50% compared to the reference concrete [73]. The decrease of initial and final setting times with an increase in curing temperature had been previously reported by Ozgur et al.[74], with the longest setting time observed in FA concrete. In this study, the setting times calculated from the proctor penetration test (ASTM C403) showed that a temperature increase within the range of 6 to 80°C decreased the setting times of concrete with FA up to 50% cement replacement. HVFA concrete containing 80% FA had significantly longer initial and final setting times, ranging from 12 to 14 hours and 15 to18 hours, respectively [75].

At a replacement level of up to 30%, Yurdakul et al. [76] also noted a slight increase in setting time, with a w/b ratio rising from 0.44 to 0.45. It was found that the increase in setting time in the class C FA mixture was greater than that in the class F FA mixture, possibly because of sulfate balance effects, according to the authors. Thus, the study suggests that class C FA can be employed effectively in concrete pavements in hot weather in order to slow the rate of setting.

The experimental results [77] showed that due to the packing effect of the finest FA particles in the mortar, the setting time of the mortar decreased as the fineness of the FA particles increased. The study also found that the longer the setting time for the higher FA levels.

The studies carried out by Elmrabet et al. [69] on FA cement, with up to 45% FA replacement, demonstrated that FA delayed the initial and final setting times compared to OPC. This is because FA in an aqueous solution increased the SiO_2 level, which reacted with water to form mono silicic acid saturated solution and developed an endothermic reaction which caused lower hydration of the blended cement.

2.2.2.3 Workability

Nath et al. [78] demonstrated that as the concentration of FA increased, the slump increased. In comparison to the reference concrete, an increase in slump height of 16.67 and 6.67% was recorded with 30% and 40% FA substitution, respectively, at a 0.29 w/b ratio. As the FA proportion increased from 20 to 30%, the slump height of the concrete decreased by around 8% to 20%. Siddique [79] reported that slump heights in HVFAC increased by 20, 25, and 35 mm, respectively, as compared with the control sample, at replacement levels of 45, 50, and 55% FA

According to Antoni et al. [80] a flow table test conducted with ASTM standards indicated that using up to 30% FA as a replacement for cement increased the workability of fresh mortar. The presence of FA also reduced the superplasticizer (SP) demand. According to a comparative study [81] of mortar and concrete with wet and dry FA of up to 30%, the wet FA was more workable than a cement-only mix. At the 30 and 50% FA replacement levels, the slump height increased by 33.33 and 83.33% at 0.5 w/b and 28 and 85.7% at 0.4 w/b, respectively, attributed to the reduced viscosity associated with higher FA concentration, which resulted in enhanced flowability and slump [82].

However, according to the findings of Funtu et al. [83] replacing cement with FA by up to 10% increased the slump values. In contrast, substituting more than 10% of the cement with FA reduced the workability of fresh concrete. Conversely, due to the dispersion of cement particles by SP, slump values of concrete with SP increased while partial substitution of cement with FA was up to 20%.

The workability of concrete with recycled coarse aggregate (RCA) increased as the percentage FA replacement level increased. Slump height increased by 0, 14.2, and 21.42% when FA was replaced with OPC by 20, 35, and 50%, respectively, compared to recycled aggregate concrete (RAC) without FA [84]. Kurda et al. [85] observed that when 30% or 60% FA was used in place of cement in RAC, the amount of water required to achieve the desired slump value of the mix with or without SP decreased. Another investigation [86] found that adding 10, 20, and 30% FA as cement replacement increased slump height by 30, 60, and 80 mm, respectively, compared with control RAC.

In their study Yurdakul et al. [76] found that increasing the replacement dosage of class F FA for a given w/b ratio resulted in improved workability of binary mixtures, attributed to the fact that class F FA reduced friction between particles. At 8% nominal air content, binary mixtures containing 15% and 30% class F FA produced the highest slump of 280 mm. Furthermore, class F FA admixed concrete had better workability. Additionally, the study found that increasing air content at a constant w/b ratio resulted in a modest increase in workability. According to a study on the influence of FA and plastic waste on concrete [87], when 20% FA was combined with 0.6% shredded polythene, the compaction factor increased from 0.91 to 0.931 compared to the reference sample.

According to the above studies, increasing FA dosage in OPC improves workability for various reasons, including that FA contains smooth spherical fine particles that act as SP and miniature ball bearings that release trapped water within cement particles and provide lubrication [85][88]. FA shortens friction between aggregate and concrete and reduces the viscosity of the mix, which also contributes to improved workability [82]. According to Paliwal et al.[87] the FA particles are spherical, and they coat and lubricate the aggregate particles, reducing friction between the aggregates and between the concrete and the supply pump. This may increase the workability and pumpability of concrete. Furthermore, FA particles adsorb on the surfaces of oppositely charged cement particles, preventing them from flocculating. As a result, a large amount of the water is released, thus lowering the water demand for particular workability.

2.2.3 Effect of FA on Properties of Hardened Concrete

2.2.3.1 Compressive Strength (CS)

According to Hassan et al. [48] 30% FA concrete had 74% OPC concrete CS after one day and 100% OPC concrete strength after 28 days. Interestingly, the CS of 30% FA concrete and 10% SF concrete was 107 and 109%, respectively, compared to OPC concrete after one year, indicating a general trend of increasing strength with age, and this is to be related to the noticeable reduction in porosity in FA concrete after 28 days. Fraay et al. suggests that the pozzolanic reaction of the FA in the PC paste can begin only after one or more weeks, when the pore water has sufficient alkalinity for dissolving FA particles. However, Rao et al.[89] reported that even at the age of 90 days, fly ash roller compacted concrete (FRCC) with up to 60% FA had lower strength than the reference mix.

Xu et al.[90] also reported a decrease in 7 days CS as FA level increased in pavement concrete. The control sample had a higher 7 days CS than the FA admixed sample. The 14 days CS of 5% type I FA (SSA 3800 cm^2/g) concrete, on the other hand, was similar to that of the control concrete but less than that of the concrete containing slag. According to the test results, the concrete with 15% type I FA had better strength at 28 days than the concrete with 5% type I FA, while the control specimen had the lowest strength. However, of all the samples examined, the type II FA (SSA 3100 cm^2/g) performed poorly at all phases of CS. The activity of admixtures mostly influenced the rate of hydration. Slag had higher activity than type I FA, while type II FA had the lowest activity and required a longer period to hydrate. The study summarises that the activity of supplementary cementitious materials (SSMs), their dosage, and their age determine the CS. Yazici et al. [32] observed that the fineness of the FA has an effect on the CS of concrete at an early age, as the study found that the concretes with the highest degree of fineness had the highest CS at an early age. A similar trend in 28 days of CS according to the particles had been reported by Bicer et al. [91]

Barbuta et al. [92] studied the combined effect of FA and glass and polyester fibers on cement concrete properties and observed that the FA dosage and type of fiber influenced the concrete's mechanical properties. The concrete with 10% FA and 0.25% glass fibers had the highest CS among the FA admixed concretes, while it was slightly lower than that of the reference concrete. However, the CS of concrete dropped as the FA dosage increased, according to the study.

According to Iqbal et al. [93] when the FA content in self-compacting concrete (SCC) increased from 100 kg/m^3 to 125 kg/m^3, the CS increased by 13.5% but decreased by 4.5% when the FA dosage further increased to 150 kg/m^3 and this strength improvement was more noticeable at 7 and 28 days. The reason for the increase in CS at a particular FA dosage could be that the optimum dosage of FA was required to fill the pores within the concrete. Mehmet et al. [94] demonstrated that the CS of SCC decreased as the FA content increased. By substituting 60% FA for cement, the CS was reduced by approximately 40%. However, the combined use of mineral admixtures appeared to mitigate this negative effect of FA as the ternary concrete with 10% FA and 10% ground granulated blast furnace slag (GGBS) attained the maximum CS of all samples. Another experiment [95] on SCC demonstrated a similar early strength drop as FA dosage increased; however, after 130 days of curing, adding FA up to 40% enhanced SCC strength but remained lower than the control sample without FA. According to Khatib [96] a high percentage of FA can be utilized to generate SCC with sufficient strength since the study found that using up to 60% FA as a cement substitute resulted in the strength of up to 40 N/mm^2.

Sadrmomtazi et al. [97] investigated the effect of FA in concrete with SF and found a decrease in 28 days CS as FA content increased; however, the CS of concrete with 10% FA was the same as that of reference concrete at 7 days and increased up to 14% in the long term. Additionally, it was observed that introducing 5% SF into FA increased CS even at early ages and that combining 20% FA with 5% SF resulted in a 20% increase in 90 days strength over the control sample. This is because the addition of finer SF particles enhanced the pozzolanic reaction with calcium hydroxide (CH).

A study of HVFA concrete [96] found a 30% increase in CS for 20 MPa concrete with 35% FA after 14 days compared to the reference sample, although it was nearly the same after 7 days. At 91 days, however, the increase was only 4%. At 14, 28, and 91 days, the strength of 40 MPa concrete with 35% FA increased by 0, 29, and 28%, respectively. 60 MPa concrete with 35% FA, on the other hand, showed increases of -9, -3, and 5% at 14, 28, and 91 days, respectively. Compared to reference concrete, the 60 MPa sample of 50% FA concrete demonstrated a 9% improvement in CS at 28 days and 1% at 91 days. Results showed that a larger HVFA replacement ratio resulted in a slight loss of CS. Previously, Siddique [98] also observed that replacing 35, 45, and 55% of cement with class F FA lowered the CS of HVFA concrete by 32, 43, and 48% at 28 days, respectively, and with curing age, the strength increased. Siddique [79] also concluded that concrete with 40, 45, or 50% FA content was strong enough to be used in reinforced cement concrete construction, even at 28 days. Sounthararajan and Sivakumar [99] suggested that FA concrete would have the same 28-day CS as conventional concrete after 56 days of curing. A CS of 37 MPa was achieved by replacing cement with 40% FA, which is acceptable as far as waste material utilization is concerned, according to Saravanakumar and Dhinakaran [100]. The use of law and high calcium FAs at up to 70% volume resulted in a self-consolidating concrete with an acceptable CS [101]. According to this study the

HVFA self-consolidating concrete showed significant reductions in 28-day CS, however, these reductions were partially offset later on.

McCarthy and Dhir [102] suggested that concrete with typical design strengths can be produced with high FA levels. It may, however, result in early strength issues that might be critical in certain aspects of the construction process. Therefore, the study also suggests that FA can be used with rapid hardening cement or low energy clinker to address early strength deficits. Filho et al. [59] reported that in order to achieve the same CS at 91 days as the reference concrete, the w/b ratio needed to be reduced in the concretes containing 50% of FA. In SCC, incorporating high volume of coarser FA reduced its water requirement [103]. The degree to which FA reacted at various curing ages depended on the FA content and w/b ratio of the paste, according to Lam et al. [31]. Additionally, they noted that using a lower w/b ratio while preparing HVFA concrete could also reduce strength losses.

2.2.3.2 Splitting Tensile Strength (STS)

Jena et al. [104] reported that concrete samples with 10% FA and 20% silpozz as a substitute for OPC showed the highest rates of increment in split tensile strength (STS) with 24 and 16.85% respectively at 28 and 90 days compared to the control concrete. As FA levels increased, STS increased less even with high levels of SP at an early age. Praveen Kumar and Ravi Prasad [105] reported that incorporating 10% LS and 8% SF with 15% FA had increased the STS by 19.54, 12.46, and 13.35 % in 30, 50, and 70 MPa concrete, respectively. According to the study, the particle size and surface area had a significant effect on the rate of reactivity. The additional CSH gel formed in the presence of LS resulted in higher strength. Sadrmomtazi et al. [97] on the other hand, added SF alone with FA and found a rise in STS. At 28 days, the combined use of 10% FA and 5%

SF produced maximum STS, 6% higher than the control sample; however, as the FA percentage increased, STS diminished. The fineness of the FA affected the development of STS at all ages, according to Yazici et al. [32]. The finer the FA, the more STS was seen in the concrete.

Barbuta et al. [92] found that adding 0.25% polyester fiber to 10% FA concrete increased the STS. However, the study showed that the STS dropped as the FA concentration increased. As a result, the study suggested employing fibers in FA concrete subjected to tension since they performed well in split and flexure tests.

With the replacement of cement with 35, 45, and 55% FA, the STS of concrete was reduced by 23, 36, and 49%, respectively, as observed by R. Siddique [98] in concrete with a high proportion FA. However, increasing the proportion of san-fibers from 0.25 to 0.75% increased the STS of FA concrete. According to Saravanakumar and Dhinakaran [100], the 28-day TS was reduced by 33.74, 24.13 and 16.16%, while the 56-day tensile strength (TS) was reduced by only 6.64, 5.47 and 2.93% compared to the reference concrete at 40, 50 and 60% FA replacement levels, respectively.

The experimental results [93] for self-compacting high strength lightweight concrete (SCLWC) showed that increasing FA from 100 kg/m^3 to 125 kg/m^3 and 125 kg/m^3 to 150 kg/m^3 increased the STS by 26% and decreased by 0.5%, respectively. According to Soni and Saini [106] the STS increased as FA replacement levels for cement increased by up to 50% with increasing age, but declined with increasing volume of FA. According to the study, as a result of the chemical transformation of gel at high temperatures, the matrix boding was weakened and the strength decreased.

According to Hashmi et al. [107] low calcium FA concrete showed lower flexural tensile strength (FTS) and STS than plain concrete at early ages of up to 28 days, but at later ages, it was comparable to plain concrete. In 180 days, the average STS at 25, 40, and 60% low-calcium FA replacement levels were 96, 90, and 78% of that of reference concrete, respectively, while the average FTS were 90, 74, and 63% respectively. Concrete mixes containing low-calcium FA develop tensile strength at a faster rate than plain concrete from 28 to 180 days.

2.2.3.3 Flexural Strength

The flexural strength (FS) of silpozz-based marine concrete with 10% FA was observed to increase compared to the control sample. At 90 days, the rate of increase in FS of the above sample was 44.82% for normal water curing (NWC) and 49.10% for saltwater curing (SWC), respectively, compared to the control sample [104]. A ternary blend of concrete containing 15% FA, 10% LS, and 8% SF increased the FS by 20.48, 14.56, and 11.22% in 30, 50, and 70 MPa concrete, respectively [105]. According to Barbuta et al. [92] FS was increased with FA up to 40% and fiber (glass and polyester) compared to the control sample; the highest FS was found at 20% FA with 0.25% polyester fiber. However, a concrete sample with 10% FA replacement and without fibers exhibited higher FS than the reference sample, and FS decreased as the FA level in concrete increased.

The experimental results in SCLWC [93] showed that increasing FA from 100 to 125 kg/m^3 and 125 to 150 kg/m^3 increased the FS of SCC by about 10% and decreased by about 17%, respectively.

In an investigation by Xu et al. [90], at all ages up to 28 days, FS was high in concrete with type I FA (SSA 3800 cm^2/g) up to 25% replacement compared to the reference concrete sample. However, compared to the control specimen, the FS of type II FA (SSA 3100 cm^2/g) incorporated concrete was lower at 7 and 14 days but was the same at 28 days. In HVFC, by substituting 35, 45, or 55% FA for cement, the FS was lowered by 39, 48, and 56%, respectively. However, increasing the proportion of san-fibers in FA concrete from 0.25 to 0.75% increased the FS marginally [98].

2.2.4 Effect of FA on Durability Parameters

2.2.4.1 Water Absorption, Sorptivity, and Water Permeability

Saha [108] demonstrated that the concrete sorptivity decreased significantly as FA dosage and curing age increased. At 10, 20, 30, and 40% FA replacement levels, the sorptivity of the admixed concrete was 96, 87, 71, and 68% of the control concrete. The study observed that FA concrete lost sorptivity for two distinct reasons. The first is that FA has more SSA than cement, and the second is that FA reduces the thickness of the ITZ between aggregates and binders. Jena et al. [104] reported that water absorption and sorptivity increased with increasing FA content. In this study, seawater cured samples (SWC) showed less absorption and sorptivity than normal water cured (NWC) samples.

As a result of the high fineness of FA, in a F-T environment, water permeability of 40% FA concrete was 26% lower than that of plain concrete, which is likely due to its enhanced reaction with the products liberated during the hydration process. Secondary or extra CSH gel produced in the presence of fine FA particles filled all of the pores inside the concrete specimen, making it dense and compact; as a result, the permeability coefficient reduced as the FA content increased up to a certain level [109].

It was reported by [94] that the ternary blend of PC, FA, and blast furnace slag (BFS) exhibited a lower sorptivity index than the quaternary blend of PC, FA, BFS, and SF and the control sample. As the FA content increased up to 60%, the water permeability of the concrete decreased, and this reduction was 50% at 60% FA content compared to the control concrete. SCC showed increased water permeability as FA content increased

[95][96]. However, at 56 and 130 days of curing, water absorption of SCC with FA up to 80% exhibited less than 2% water absorption [96].

Using FA as the cement replacement, the water absorption, permeable voids, sorptivity, and water permeability increased with increased FA dosage compared to reference concrete. While FA as an aggregate replacement, the value of the above parameters declined as FA percent increased but remained lower than the reference sample at all FA dosages. However, all the mixes exhibited less than 3% water absorption [110].

Based on [91] the water absorption of cement increased as the grain diameter, and FA percentage increased. Studies showed that water absorption values are less than their critical value (30%) at 10% and 30% FA ratios. However, the water absorption at 50 to 90% FA replacement levels was more than 30%, indicating that FA concrete shouldn't be used where it is exposed to water and against inner wall elements where inner plaster, isolation plaster is used as low-density construction materials.

2.2.4.2 Carbonation

An experimental study [95] showed that with the increase in FA content in SCC, carbonation resistance decreased. A similar finding was reported in [111][112]. This is because the use of FA reduces the concentration of carbonatable constituents (CH and CSH); as a result, total CaO decreases due to the higher carbonation rates [113].

According to Burden et al. [114] after one year of curing, concrete containing FA at replacement levels of 30, 40, and 50% exhibited higher carbonation rates than concrete without FA. Kurda et al. [115] reported that using 30% and 60%, FA increased the carbonation depth in concrete with a high proportion of FA and RCA by 5 and 6 times, respectively. Additionally, the study revealed that using RCA and FA in combination was more effective at preventing carbonation. Concrete's alkaline reserve decreases due to cement consumption and the pozzolanic reaction of FA. However, as the carbonation time increases, the CSH gel produced by the pozzolanic reaction further fills the pores, increasing the concrete density and thus its resistance to CO_2 intrusion and improving the carbonation resistance [116], [117].

Additionally [115], [118], [119], [120] reported that with the combined use of RCA and FA, the carbonation coefficient increased but remained lower than the individual addition of FA and RCA. Because the quantity of $Ca(OH)_2$ in RCA significantly compensates for the amounts of $Ca(OH)_2$ consumed by SiO_2 in FA, indicating using FA with RCA in concrete is beneficial. Bouzoubaâ et al. [121] reported that the depth or rate of carbonation varies more with the CS of the concrete, the FA concentration, and, to a lesser extent, the moist-curing period than with the type of FA used.

2.2.4.3 Sulfate attack

Sulfate attack is the expansive reaction between penetrating sulfate and hardened binder phases [122] and is one factor that affects concrete durability, as it can cause concrete structures to expand, crack, deteriorate, and deform [123]. The expansion of the concrete is due to the formation of ettringite and gypsum [124][125]. Since the pozzolanic reactions reduce the quantity of CH and increase CSH, the pozzolanic cement performs better in sulfate solutions [126]. Liu et al. [127] reported that the addition of FA significantly increased resistance to sulfate attack, owing to FA's pozzolanic reaction; when 40% FA was added, the sulfate resistance was better than the sample with 20% FA. A lower expansion of 10% FA admixed concrete compared to control concrete exposed to 5% Na_2SO_4 and 4.2% $MgSO_4$ solution was reported by [128] for different curing periods up to 300 days.

The conversion of CH to gypsum occurs simultaneously with the formation of magnesium hydroxide, which is insoluble and reduces the alkalinity of the system. As CSH no longer has hydroxyl ions in the solution, it becomes unstable and is also attacked by the sulfate solution. Therefore, concrete is more susceptible to the magnesium sulfate attack [129]. Vishwakarma et al. [130], reported that FA concrete performed better in a sulfate-rich environment than the concrete modified with nano-particles, indicating that nano-particle FA concrete is not ideal for sulfate-rich environments. An improved sulfate resistance was observed in mortars blended with 25% FA because of reduced permeability by the pozzolanic action of FA, and reactive aluminates, according to Nei et al. [131]. It was also reported by [132] that the use of FA subsides the amount of C3A produced in concrete to minimize the sulfate attack by lessening the undesirable gypsum and ettringite development [133]. In addition, because of the binder's lower concentration of C3S and C2S, CH production in the hydrated binder was reduced. Furthermore, due to CH consumption during the pozzolanic process, the CH content of the hydrated binder decreased further. As a result, the CSH refines the ITZ and matrix pores by lowering permeability [129], [134]. It is also reported by Nei et al. [135] that sulfate diffusion coefficients are reduced with the use of FA in concrete, thus influencing sulfate resistance, suggesting that chemical reactions of FA must be considered for predicting the service life of concrete under sulfate attack.

Additionally, FA type also affects sulfate attacks. The cement paste with 20% class F FA exhibited 35% reduced expansion, while class C FA and class O (neither class F nor class C) FA showed expansion similar to OPC paste when exposed to 200 days in a sodium sulfate solution [136]. With the use of class F FA, the microstructure of ITZ improved, and 50% of the air void was filled up by pozzolanic reaction products [137].

2.2.4.4 Corrosion Resistance

According to Shaikh et al. [138] mass loss of rebar due to corrosion in cement concrete was approximately 20% less than the control sample at a 40% FA replacement level. The combined use of 8% UFFA and 32% FA as an OPC replacement resulted in a mass loss of only 7.16%. Incorporating HVFA and UFFA improved the corrosion resistance of admixed concrete by reducing porosity and chloride penetration. Jiang et al. [139] reported that large volume low, quality fly ash (LVLQFA) concrete effectively resisted corrosion when tested in 5% Na_2SO_4 and 5% HCl solutions compared to the control sample at 56 days and 118 days curing intervals.

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

Boa at al. [141] reported that by replacing 15, 30, and 45% of the FA, corrosion currents decreased, and the time for concrete deterioration to occur increased significantly. However, they were more pronounced in the water-cured samples when compared to the air-cured samples at 28 and 56 days. Due to incomplete pozzolanic reactions in air-cured FA concrete, the concrete became more permeable. Revathi et al. [86] also found that corrosion currents decreased as the percentage of FA replacement in RAC increased from 10% to 30%, attributed to the fineness of FA and its ability to fill the pore spaces in concrete structures. The steel passivity in reinforced concrete was reduced, according to Quraishi et al. [142] because of a reduction in $Ca(OH)_2$ caused by the pozzolanic reaction of FA, and, at the same time, extra secondary cementitious material was produced, which filled the pores of the concrete, making it thick, and, therefore, providing better corrosion resistance to reinforcement.

Praveen Kumar and Ravi Prasad [105] observed a high resistance against corrosion in the ternary admixed concrete of 15% FA, 10% LS, and 8% SF compared to control concrete. The study also found that as concrete grade increased, corrosion resistance increased due to the micro filler effect of the admixtures.

2.2.4.5 Effect of Acid Exposure

According to Torii and Kawamura [143] substituting FA for cement significantly improved the mortar's resistance to sulfate attack, owing to the mortar's high impermeability and low CH content. However, the efficiency of FA in improving the resistance to sulfate solution attack varied according to the type of cation, Na^+ or Mg^{2+} in sulfate solutions resulting formation of ettringite or gypsum. The replacement of cement by FA could not effectively prevent acid-type deterioration involving scaling and softening of the mortar in a very low pH of 2% H_2SO_4 solution. The sulfate-generated expansion of FA mixes was reduced when the FA replacement percentage was more than 30% when exposed to a 10% Na_2SO_4 solution. However, when exposed to a 10% $MgSO_4$ solution, higher FA replacement was not always effective in preventing the magnesium-ion attack because CSH gel produced during the pozzolanic reaction was more susceptible to the magnesium-ion attack.

When FA content increased from 0 to 70%, Aydin et al. [144] observed a decrease in the percentage of strength loss in the 60 days of steam-cured samples from 58 to 21%, indicating an improved acid resistance in FA concrete. However, no difference in strength loss was observed in samples in standard curing when FA content increased. The study also observed a similar trend in weight loss. According to Verma et al.[145] also, FA had proven to be a useful material for making concrete in aggressive environments, as the study observed a lower loss, compared to plain concrete, in CS in HVFAC with 50% FA in 0.1 N and 0.2 N concentration sulphuric acid exposure conditions. The improvement in acid resistance of FA concrete is attributed to the additional formation of CSH due to the pozzolanic reaction between FA and CH liberated during the hydration process [144]. In another study [146], concrete with only 25% FA and PCE-based SP performed better against acid attacks than control specimens without SP. However, the difference in a percentage loss of CS between the samples without SP was negligible.

2.2.5 Ground Granulated Blast Slag (GGBS)

The manufacturing of iron and steel results in the creation of a by-product known as ground granulated blast furnace slag [147], [148]. It has both strong pozzolanic capacity and cementitious qualities, and it has a glassy consistency and granular form. Due to the fact that it is a waste product from the manufacture of iron and steel, as well as the fact that its use in the manufacturing of concrete has been the subject of a great deal of research, this substance is environmentally friendly [149], [150]. The use of ground granulated blasted slag (GGBS) as a supplementary cementitious material (SCM) has the potential to partially replace cement in a concrete mixture. This has the potential to offer a number of advantages, including improved workability, decreased heat of hydration, decreased shrinkage, and improved durability [151].

2.2.6 Effect of GGBS on fresh cement and concrete

This section gives a quick overview of how GGBS affects the properties of freshly mixed concrete and how much of an impact it has. First of all, it should be highlighted that the effect of GGBS varies greatly depending on how much replacement is added to concrete mixtures.

2.2.6.1 Setting Time

When GGBS is used as a partial replacement for Portland cement in concrete mixtures, an increase in setting time is often anticipated. The replacement ratio , the ratio of water to cementitious ingredients, the properties of Portland cement, and the initial temperature of the concrete all have an impact on how long it takes for the concrete to set [152] . Concrete made using GGBS typically takes longer to set than concrete made with Portland cement. Generally speaking, setting time rose as GGBS content grew [152].

According to [153] GGBS concrete needs more time to set than Portland cement concrete, most likely because of the smooth and glassy particle shapes of GGBS. With a growing percentage of GGBS replacements, the setting time likewise grows longer. Low ambient temperatures have an impact on the GGBS concrete's setting timeframes.

The effect would be more noticeable at high concentrations of GGBS and/or cold temperatures, according to [154] A longer setting time is helpful since there will be fewer joints because the concrete will be usable for longer duration. In warm temperatures, this is particularly helpful [12].

2.2.6.2 Workability

In-depth research on workability proposed that a cementitious matrix including slag cements displayed enhanced workability as a result of the higher paste concentration and higher cohesiveness [155].

It should be noted that using GGBS in place of Portland cement increased the slump value. Due to micro-filling voids inside the concrete aggregate, additional cement paste resources are available to reduce internal friction among concrete components, resulting in more flow-able concrete [155]. Additionally, a study asserts that improved GGBS particle dispersion is reason for the greater slump [156] . The workability of mortar declined as GGBS surface area rose, according to the authors of [157], and higher slag fineness had no appreciable effect on it. The flowability of the ultra-high-performance concrete (UHPC) mix can be significantly improved by increasing the ratio of OPC to GGBS, according to studies. From this, it can be inferred that the improvement in flow is significant up to a 40% substitution ratio of GGBS and that the improvement in flowability is not taken into account above 40% [1]. On the other hand, as the amount of GGBS is increased, the flowability of concrete mixes decreases. Concrete's decreased flowability may be attributed to more water absorbing into the material. Additionally, the results of the slump test demonstrate that when GGBS content rises, the workability of the concrete declines. This might be the outcome of the GGBS's greater propensity to absorb water when compared to natural fine aggregate. Consequently, the use of superplasticizers is suggested to achieve the required slump value when utilizing more than 40% GGBS in concrete. Additionally, two of the most significant characteristics that affect the flowability of concrete are the rough surface texture and higher water absorption of GGBS [158].

2.2.7 Effect of GGBS on Properties of Hardened Concrete

2.2.7.1 Compressive Strength (CS)

In an experimental study, it was discovered that CS improved with GGBS up to a 20% replacement gradually lost strength as curing ages increased, reaching its maximum strength at 20% GGBS substitution. Strength dramatically decreased after GGBS was replaced with concrete at a 20% replacement with an 80% replacement of GGBS, demonstrating significantly lower CS than concrete that had been replaced with GGBS at a 20% replacement [12]. Another study found that adding GGBS raised the CS of concrete by up to 20 percent, but further GGBS additions were not successful due to a lack of flowability [9]. The creation of new binding compounds, such as CSH, which had a beneficial effect on CS, was brought about by the pozzolanic interaction of the silica dioxide in GGBS with the calcium hydrate of cement [2]. Concrete can continue to gain strength over time with the addition of the extra binder created by the GGBS reaction with available lime. However, at higher dosages (more than 20% by weight of cement), strength declines due to the dilution effect, which is brought on by the alkali-silica reaction because there is more unreactive silica accessible as a result of the higher percentage of GGBS used in concrete [14]. Additionally, GGBS fills in the spaces in the aggregate resulting in denser concrete, which increases the CS of concrete [9]. However, at larger doses of GGBS (more than 20%), a drop in CS was found owing to deficient flowability, which enhanced compaction efforts resulting in more pores in the concrete, ultimately lowering the CS of the concrete. A study [11] reported that the strength of mortar containing GGBS is related to both the particle size distribution and surface area of GGBS. The early strength of the mortar rose according to the quantity of fine GGBS particles even if GGBS had the same surface area. The strength of the mortars over time increased with the amount of GGBS particles present.

Furthermore, since the pozzolanic reaction occurs slowly, the CS of concrete containing GGBS also depends on curing days. According to the research findings, the CS of the concrete using GGBS as fine aggregate is comparable to that of the reference concrete at early ages. However, owing to the reactivity of slag, the higher the amount of slag replaced by sand, the greater the CS of the concrete is likely to be at 365 days [15].

2.2.7.2 Split Tensile Strength (STS)

Similar to the CS, the STS of concrete increased with GGBS replacement up to 20% and then gradually decreased, reaching its maximum STS at 20% of GGBS replacement at all curing ages. However, the STS dramatically decreased with a GGBS replacement of more than 20%, and even at 80%, the STS was much lower than in control concrete (concrete without the addition of GGBS) [1]. The STS of concrete was likewise shown to rise with the substitution of GGBS up to a 20 percent level, but the STS decreased due to a lack of flowability after that point, or beyond 20 percent [155]. The pozzolanic activity of GGBS, which helps to reduce the presence of holes and improves the interface properties, may be a possible explanation for the improvement in STS. Another study found that the STS results of high-volume GGBS at 56 and 90 days show that the at concrete's primary stage strength does not show any appreciable improvement when compared to the later age results at 56 and 90 days. The fact that GGBS first responds slowly to normal water curing conditions is one factor that could apply. However, STS was significantly enhanced by curing at a high temperature [1]. However, when the amount of GGBS was raised by more than 20%, the diluting effect caused the STS to decrease, which triggered an alkali-silica reaction. The alkali-silica reaction (ASR), which happens when unreactive silicon dioxide combines with alkali, occurs when a greater dosage of GGBS is employed [155].

2.2.7.3 Flexure Strength (FS)

Calcium silicate hydrate (CSH) is a supplemental cementitious gel that is created by the pozzolanic interaction of silica in GGBS and calcium hydrate in cement and has a favorable effect on FS [155]. Previous research indicates that the strength of the binder has the biggest impact on FS. Aggregates try to move apart when under tensile tension. The additional binder created by the GGBS[159] increases resistance. The FS decreased due to the dilution effect when the amount of GGBS was raised by more than 20%, however, and this resulted in an alkali-silica reaction. When more GGBS is utilized, it is discovered that unreactive silica is easily accessible and combines with alkali to produce the alkali-silica reaction [155]. The results of one study also showed that the FS of concrete mixes rises as the proportion of GGBS in the mix does. For a control mix without GGBS, the FS of concrete at a water to binder ratio of 0.45 is 4.216 MPa. Additionally, when GGBS is replaced at 20%, 40%, and 60%, the FS rises to 4.367 MPa, 4.47 MPa, and 4.61 MPa, respectively, which is 3.58 percent higher, 6.02 percent higher, and 9.34 percent higher than the control mix. The neutralization of calcium hydroxide crystals enhances the pozzolanic activity of GGBS in the concrete. The FS of the concrete is raised as a result [158].

2.2.8 Effect of GGBS on Durability Parameters

2.2.8.1 Permeability

Concrete's permeability affects its longevity because it controls the rate at which moisture and harsh chemicals can penetrate. Concrete that has a lower permeability resists cracking better.

The pozzolanic reaction with secondary cementitious materials (CSH), which enhanced the binding property of mortar and resulted in lower permeability, is what causes the decrease in permeability of concrete containing GGBS. Additionally, the micro filling effect of GGBS, which fills the gaps in the aggregate, results in a more compact mass, lowering the permeability of the concrete in the process. The permeability of the concrete is positively impacted by the combined pozzolanic reaction and micro filling voids. A higher dose of GGBS (above 20 percent), according to one study, may cause more voids in concrete because it is harder to work with [155]. Concrete's permeability tends to increase as there are more voids present.

2.2.8.2 Carbonation

In accordance with [17], the rate of carbonation in concrete increases as the amount of blast furnace slag in the mix increases. [18] suggests that the deeper carbonation observed in blast furnace slag concrete may be attributed to the lower amount of Ca(OH)2 in the paste, requiring a smaller amount of carbon dioxide to produce CaCO3. An experimental study indicated that replacing 65% of the cement with blast furnace slag resulted in a significantly deeper carbonation depth compared to a 50% replacement [19]. However, the incorporation of GGBFS was found to reduce carbonation depths only at specific replacement levels. Study [20] reports that the depth of carbonation in blast furnace slag concrete is higher than in OPC mortar mix, and the carbonation rate increases as the slag replacement level increases from 30-70% in mortar and 50-80% in concrete [21].

2.2.8.3 Acid Attack

According to [160], adding more slag to Portland cement-slag mortars significantly boosted their sulfate resistance. In a study, the mechanical behavior and durability of GGBS concrete were examined by partially replacing cement with GGBS at rates of 30%, 40%, and 50% for M20 and M40 grade concrete. Durability studies were conducted using hydrochloric acid and sulfuric acid. The results showed that replacing cement with GGBS increased the strength of both M20 and M40 grade concrete and improved the workability of the concrete as the GGBS content increased. When compared to normal concrete, the compressive strength values of acid-affected concrete decreased, but the impact of acid on the concrete decreased with increasing GGBS percentage. Additionally, the effect of HCl on the strength of the concrete was less than the effect of H_2SO_4, and the impact of HCl was more significant than the impact of GGBS concrete affected by H_2SO_4 [161].

2.2.8.4 Corrosion Resistance

In acidic environments, the corrosion resistance of GGBS concrete is also improved. Acidic attacks on concrete can lead to the corrosion of steel reinforcements and the degradation of the concrete matrix. However, the use of GGBS in concrete can reduce the rate of corrosion by minimizing the permeability of the concrete and providing an alkaline environment that inhibits the corrosion process [162].

Studies have shown that the use of GGBS in concrete can significantly improve its resistance to various forms of corrosion, such as chloride-induced corrosion, acid attack, and sulfate attack. Therefore, the use of GGBS in concrete can lead to more durable and longer-lasting structures, particularly in harsh environments or structures subjected to aggressive chemical exposures [163].

In a study conducted by researchers [26], the aim was to investigate the durability of concrete that contains ground granulated blast furnace slag (GGBS) and the corrosion behavior of reinforced concrete beams under different loading ratios. The experimental setup included prismatic beam specimens with dimensions of 150 mm × 150 mm × 900 mm that were exposed to 3.5% NaCl solution and sustained loading equivalent to 37% and 75% of the ultimate load. To accelerate the corrosion process, a direct current of 1 mA cm^{-2} was applied. Open circuit potential (OCP) and direct current polarization resistance were measured to evaluate the corrosion of rebar. The deflection and residual loading rigidity of the beams were measured, and rapid chloride penetration test (RCPT) and permeability tests were conducted on GGBS concretes.

The results of the study indicated that the partial replacement of cement with GGBS had inhibiting effects on both the total charge-pass and permeability of the concrete. The addition of slag and sustained loading significantly influenced the corrosion rate and flexural rigidity of reinforced concrete beams. These findings suggest that the use of GGBS in concrete mixes can improve their durability and resistance to corrosion. Therefore, incorporating GGBS into concrete mix designs could lead to more sustainable and long-lasting structures. However, further research is necessary to optimize the amount of GGBS used and its effects on the properties of concrete under different loading conditions.

2.2.9 Mirco Silica (MS)

In the silicon and ferrosilicon industries, silica fume (SF) is a byproduct. When high-purity quartz is converted to silicon at temperatures up to 2000 °C, SiO_2 vapors are produced. These vapors then condense into minute non-crystalline silica particles in the low-temperature zone. Non-crystalline silica comprises 85–95% of the byproducts of silicon metal manufacturing as well as ferrosilicon alloys with silicon concentrations of 75% or more. Having a substantially lower silica content and being less pozzolanic, the by-product of the manufacturing of ferrosilicon alloy with 50% silicon is much less conductive. Condensed silica fume, micro silica, volatilized silica, and silica dust are other names for silica fume. Either superior white or grey silica fume is available.

2.2.10 Effect of MS on Fresh Cement and Concrete

2.2.10.1 Workability

According to [164], adding 10% silica fume to a lean concrete mix (100 kg/m3) of cement decreased the water need. Even with a 5% addition of silica fume, standard structure concrete requires more water to maintain a steady slump. Superplasticizer is used to preserve the desired slump and silica fume up to 10% is added as an additive to produce concrete with extremely high strength and durability.

Using silica fume, [70] created high-performance concrete. The water-cementitious ratio was 0.35, and the silica fume content was 0, 6, 10, and 15%. It was found that mixes with a higher silica fume content tended to need larger superplasticizer dosages. The relatively small particle size of silica fume, which results in some of the superplasticizer being adsorbed on its surface, has been ascribed to the higher demand for superplasticizer with concrete containing silica fume.

2.2.11 Effect of MS on Properties of Hardened Concrete

2.2.11.1 Compressive Strength

The compressive strength of the mix is significantly altered when silica fume is introduced to concrete. This is mostly attributable to improved aggregate-paste bonds and improved microstructure.

According to [165], the increased strength of silica fume concrete over silica fume paste is due to the altered function of the aggregate in concrete. The aggregate serves as an inert filler in cement concrete, however composite concrete is less strong than cement paste due to the presence of a weak interfacial zone. But with silica fume concrete, the fume's presence strengthens the cement paste aggregate bond and creates a less porous, more uniform microstructure in the interfacial zone, eliminating this weak link. Given that aggregate strength is greater than cement paste strength, silica fume concrete is stronger than silica fume cement paste.

The impact of silica fume (0, 6, 10, and 15 percent) on the compressive strength of high performance concrete up to the age of 400 days was examined by Mazloom et al [166]. They found that, the silica fume concrete was 21% stronger than control concrete at 28 days and the compressive strength development of concrete mixtures containing silica fume was negligible after the age of 90 days. However, the strength of control concrete increased by 26% and 14% after one year compared to its 28 and 90-day strengths, respectively. The rapid development of an inhibiting layer of reaction product, which prevents further reaction of silica fume with calcium hydroxide after 90 days, was also mentioned by [167] as a possible explanation for the difference in strength development between OPC concrete and silica fume concrete.

Compressive strength of high performance concretes was studied by [168]. It was found that, increasing the dosage of superplasticizer from 8 to 18 percent resulted in a decrease in water-to-cement ratio (w/c) from 0.31 to 0.26 and increased concrete compressive strength from 86 to 97 MPa, and the highest compressive strength of 91 MPa was attained at a silica fume concentration of 15 percent.

The compressive strength of concrete reinforced with steel fibres and silica fume with hooked ends was studied by [7]. Steel fibres' aspect ratios (l/d) were 65 and 80, and their volume fractions (Vf) were 0.5 and 1 percent. The percentages of silica fume in the cement were 0, 5, 10, and 15%. Table 10 contains the test outcomes. It was found that, increasing the silica fume content resulted in a sizable increase in the compressive strength of the concretes made without steel fibres. For silica fume concentrations of 5, 10, and 15%, the increases were 12, 73.4, and 85.5 percent, respectively. These results were unmistakably dependent on the higher compressive strengths of concretes produced by additions of both steel fibre and silica fume than those produced using silica fume alone; and the increasing bond strength of cement paste-aggregate interface through the filling effect of silica fume.

2.2.11.2 Splitting Tensile Strength (STS)

Hooton [169] examined the impact of silica fume on the splitting tensile strength of concretes up to the age of 182 days (Table 12). Except after 28 days, he came to the conclusion that silica fume concrete mixes did not improve the splitting tensile strength. Additionally, it was noted that the split tensile strength dropped as silica fume replacement increased.

Bhanja and Sengupta [170] investigated the effect of silica fume on the tensile strength of high-performance concrete at the age of 28 days. Five concrete mixtures were created by partially substituting silica fume for cement in the following weight ratios: 0.26, 0.30, 0.34, 0.38, and 0.42. (0, 5, 10, 15, 20 and 25 %). The splitting tensile strength was not significantly increased by very high percentages of silica fume, and the gain was negligible above 15%, according to studies.

[171] looked into how silica fume affected concrete constructed with inferior coarse particles' ability to split under tension (calcareous, dolomitic, and quartzite limestone and steel slag). The concrete samples had a coarse to fine aggregate ratio of 1.63 and a w/c ratio of 0.35. The findings showed that splitting tensile strength rose with age, with 15% silica fume cement concrete having the maximum splitting tensile strength, which was higher than plain concrete's splitting tensile strength.

Tanyildizi and Coskun [172] investigated how silica fume affected lightweight concrete exposed to high temperatures in terms of tensile strength. In mixes containing silica fume, silica fume was substituted for Portland cement to varying degrees (0, 10, 20, and 30 percent by weight). They claimed that temperatures above 200 C caused the tensile strength to begin to decline. At 200, 400, and 800 C, respectively, the splitting tensile strength of lightweight concrete containing 10% silica fume decreased by 3.11, 11.46, and 80.15 percent. At 200, 400, and 800 C, respectively, the reduction in splitting tensile strength of lightweight concrete containing 20 percent silica fume was 4.69 percent, 12.91 percent, and 78.87 percent. Additionally, at 200, 400, and 800 C, respectively, the splitting tensile strength of lightweight concrete containing 30 percent silica fume decreased by 5.8%, 40.62%, and 75.08%. They came to the conclusion that silica fume used as an additive kept concrete's tensile strength from declining.

2.2.11.3 Flexural Strength (FS)

The impact of micro silica on the flexural strength of high performance concrete was researched by [170]. (HPC). The cement in five series of concrete mixes was partially replaced with silica fume of equal weight at w/cm ratios of 0.26, 0.30, 0.34, 0.38, and 0.42. (0, 5, 10, 15, 20 and 25 percent). It was found that silica fume appeared to have a more dramatic impact on flexural strength. Even very high concentrations of silica fume significantly increased flexural strength. Additionally, it was discovered that the flexural strength steadily increased as the silica fume replacement percentage increased.

The flexural strength of concrete adding hooked steel fibres and silica fume was assessed by [173]. Steel fibres had volume fractions (V_f) of 0.5 and 1 percent and aspect ratios (l/d) of 65 and 80. Results for flexural strength are shown in Table 14. By incorporating silica fume and steel fibres, the flexural strengths of the composites were shown to significantly increase. For each silica fume percentage, it was discovered that the flexural strengths of concretes including 1 percent steel fibre were higher than those of concrete having only 0.5 percent steel fibre.

The effects of aggregate type on the flexural strength properties of high-strength silica fume concrete were investigated by [174]. There were five main types of aggregate used: gabbro, basalt, quartzite, limestone, and sandstone. On a bulk basis, cement replaced silica fume to a ratio of 15% at 0.35 water to binder ratio. The superplasticizer accounted for 4% of the mass of the binder. They demonstrated that flexural tensile strength rose with longer curing times, with gabbro concrete exhibiting the highest flexural tensile strength and sandstone concrete exhibiting the lowest.

2.2.12 Effect of GGBS on Durability Parameters

2.2.12.1 Permeability

The influence of silica fume (5–20 percent by weight of cement) on the chloride permeability of concretes prepared with water-cementitious ratios of 0.4 and 0.5 were investigated by [175]. It was noticed that the chloride-ion diffusion significantly decreased as the amount of silica fume increased. This may have resulted from the inclusion of silica fume, which led significant pore refinement, or the conversion of larger size pores into smaller ones as a result of their pozzolanic reaction associated with cement hydration.

According to [169], the inclusion of silica fume reduced the permeability of concrete. The water-permeability of the control mix was 1.8×10^{-14} m/s, but the water-permeability of the concrete mix prepared with 10% silica fume was less than 1×10^{-17} m/s. It was unable to assess the permeability of silica fume concretes with increasing silica fume dosages. Silica fume significantly decreased the water permeability in lean concrete, as per [176] observation. When 10 kg/m^3 of silica fume was added to concrete, the water permeability coefficient dropped from 1.6×10^{-7} to 4×10^{-10} m/s. The latter permeability value was equivalent to that obtained from concrete having no silica fume and using 250 kg/m^3 of cement.

Soroushian and Mirza [177] observed that the chloride-ions permeability of concrete was lowered by 75% with the addition of polypropylene fibres and silica fume. Adding silica fume to the mortar made of glass fibre reinforced resulted in a 98 percent reduction in the coefficient of chloride diffusion. The favourable impacts of silica fume additions were related to the alteration of the material microstructure, which led to an increase in density and a decrease in capillary porosity as a result of reaction products including calcium silicates and calcium aluminates.

A method for forecasting the diffusivity of high strength silica fume concrete was developed by [178]. The degree of hydration, water-to-binder ratio, and silica fume replacement ratio are the primary determining elements. As the quantity of silica fume increased, the relative diffusivity of bulk paste and ITZ also dropped.

2.2.12.2 Carbonation

[179] examined the carbonation depths of field concrete with or without silica fume. To account for variations in compressive strength and length exposure in the environment, the findings were normalised. Under these circumstances, silica fume concretes had a deeper mean carbonation depth, although the variation was rather substantial. A laboratory investigation revealed that silica fume concrete had higher carbonation rates than concrete without silica fume for a given compressive strength. According to [180], the rate of carbonation is increased by the consumption of $Ca(OH)_2$ in the pozzolanic reaction, whereas it is decreased by the clogging of capillary pores. [181] discovered that mortars containing silica fume had deeper carbonation than controls. They explained this outcome as being the consequence of the pH being lowered by the pozzolanic process.

Tests by [182] were conducted with the intent of developing high-performance concrete. On the basis of ordinary Portland cement, finely ground fuel ash, and silica fume, binary and ternary blended cementitious systems were examined. PFA up to 40% was employed, and to these blends, silica fume at percentages of 0%, 5%, 10%, and 15% was added as a partial cement substitute. After two years of exposure at 20°C and 65°RH under typical atmospheric conditions, carbonation tests were made on concrete cubes of 100mm in size. Concrete produced with a w/b ratio of 0.27 was the only material used in the carbonation investigation. At the age of two years, the samples (100mm cubes) were divided into two halves. The results clearly showed that carbonation increased as PFA quantity increased, although silica fume addition on its own had no effect on carbonation.

[183] investigated the effects of silica fume, fly ash, and mineral admixtures on the performance of concrete. Fly ash and silica fume replacement levels in the concrete mixes were maintained at 15% and 10% of the weight of cement, respectively. They came to the conclusion that FA-containing concrete mixes had somewhat deeper carbonation than control concrete. Compared to the findings of other concrete combinations, where silica fume had no impact on carbonation, the depth of carbonation was lower in concrete mixtures that simultaneously included fly ash and silica fume. The decreased porosity was thought to be the cause of the SFAC's shallower carbonation depth.

2.2.12.3 Acid Attack

Related to the pretty small amount of silica fume employed in practise, ACI Committee 234 (1995) claims that the influence of silica fume on sulphate resistance is mainly due to the decrease in permeability than to the dilution of the C_3A content.

Concretes with and without a 15% silica fume content were the subject of field investigations by [184]. The performance of the silica fume concrete was found to be equivalent to that of the concretes made with sulfate-resisting Portland cement after 20 years of exposure, despite the fact that the ratio of water to cementitious materials was considerably higher for the silica fume concrete (0.62) than for the control (0.50).

[185] looked at the sulphate resistance of silica fume-concrete. For five years, concrete samples were partially buried in sulphate soil. Ordinary Portland cement (C_3A=8.5%) was replaced in part with mineral admixtures, and the progression of sulphate attack was assessed using a variety of techniques (visual rating, loss in mass, dynamic modulus, strength, and X-ray analysis). The sulphate resistance of the concrete when buried in the soil was found to be enhanced by silica fume, according to the results. However, owing

to the crystallisation of sulphate salt, concretes with high silica fume concentration showed increased surface scaling above soil level.

The usefulness of silica fume in reducing the harm caused by sulphate assault was researched by [186]. The mortar compositions' water/cementitious material ratios (w/cm) were 0.35, 0.45, and 0.55. Up to about a year of exposure in this sulphate environment, incorporation of 10% silica fume in OPC matrix exhibited no signs of spalling or cracking, and strength loss increased as the w/cm ratio increased. The total strength loss as well as the difference between different w/cm ratio levels was greater in mortar specimens without silica fume than in those with silica fume.

[187] created high-performance concrete mixtures with different ratios of silica fume and natural pozzolan (up to 15 percent by weight of cement). They were kept in Dead Sea and Red Sea waters, together with solutions of sodium and magnesium sulphate. The concrete mix comprising a mixture of 15% silica fume and 15% natural pozzolan (by weight of cement) demonstrated a greatest protection against sulphate attack compared to others tested in the research after one year of immersion in sulphate solution and sea water. After a year of preservation in sulphates solutions and sea waters, this mixture still had more than 65% of its original strength. The improved resistance of that mixture to sulphate attack was credited to the lime-pozzolan reaction's conversion of lime produced by the hydration of cement into extra binding material, as well as the process of pore refinement and increased densification of the transition zone. According to the findings, magnesium sulphates were more harmful than sodium sulphates, which was in line with the information found in the literature [134].

2.2.12.4 Corrosion

Using electrochemical testing on concrete samples observed over a two-year period, [188] discovered that adding silica fume (up to 15% addition to cement) increased the long-term corrosion resistance of cement. [189] noticed, adding 10 or 20 percent silica fume to ordinary cements greatly increased corrosion resistance. By raising the silica-fume percentage from 10% to 20%, they discovered barely any noticeable improvement in corrosion-initiation time.

According to [190], an iron oxide layer on typical steel reinforcing bars gets unstable when the concrete around them has a pH of 10–11 or when chloride ions come into contact with the layer. Because there was less cement present when silica fume was utilised as a cement substitute, the pH of the concrete reduced. The pH is further decreased by decreases in $Ca(OH)_2$ content brought on by the pozzolanic reaction of silica fume and alkali-pore water concentration. But since the pH of concrete does not go below 12 even when 30% silica fume is utilised, these variables have very minor influence on the passive iron oxide layer. Concrete containing chlorides has a much lower chloride diffusion coefficient and chloride concentration when silica fume is present. Additionally, the use of silica fume significantly raised the electrical resistance of concrete, delaying deterioration.

Using an accelerated impressed voltage testing system, [191] investigated the efficacy of silica fume concrete in preventing damage brought on by corrosion of embedded steel. Silica fume concrete substituted equal amounts of conventional Portland cement with 0, 10, 15, 20, and 25 percent silica. For 7 and 28 days, concrete samples were either treated with fresh water or salty water containing 4% NaCl. Resilience of concrete to corrosion-related damage was measured using the STC (susceptibility to corrosion) index. Corrosion resistance was greatly increased when ordinary concrete was blended with 10–

20 percent silica fume. STC index of control concrete (zero percent silica fume) during 7 days of curing was 16.61 × 10 $^{-4}$/Wh^{2} with fresh water and 29.32 × 10^{-4}/Wh^{2} with salty water. Up to 15% silica fume concentration, the STC index remained almost stable (the same as with 0% silica fume), however at higher doses (20-25%), the STC index drastically decreased (2.5-9.8 × 10^{-4}/Wh^{2}). Control concrete with zero percent silica fume attained an STC index of 6 × 10^{-4}/Wh^{2} with fresh water and 8.1 × 10^{-4}/Wh^{2} with salty water after 28 days of curing. At a silica fume replacement dose of 15%, the impact was at its best. STC was consistently lower during extended curing times. The STC values of the 28-day samples for the control mix were between 28 and 36 percent of those of the 7-day samples. For silica fume concrete, this proportion was substantially smaller (0.8–17%).

After being partially submerged in a 2 percent chloride solution, [192] tested high-strength reinforced silica fume-cement concrete slabs with a compressive strength of 70MPa for chloride diffusion and corrosion event. It was discovered that high-strength concrete with 10% silica fume has very excellent corrosion resistance.

To ascertain the efficiency of calcium nitrite, silica fume, fly ash, powdered granulated blast furnace slag, and disodium tetrapropenyl succinate (DSS) in mitigating corrosion of reinforcing steel in concrete, [193] carried out a long-term corrosion investigation. Single, double, and triple combinations of these admixtures were included in the mixture proportions. They came to the conclusion that a triple combination of CN, SF, and FA (or a double combination of CN and BFS), all at modest doses, was advised for the best protection against corrosion in structural concrete.

2.3 LITERATURE REVIEW ON SUPERPLASTICIZER

The polycarboxylate (PC) SP has a high-water absorption rate and long-term slump retention at a low dosage. Still, its chemical structures determine its predominant mechanism and efficiency in cement-based materials [28].

SPs were first employed in concrete in 1931 when a road construction organization in Massachusetts utilized naphthalene sulfonate formaldehyde condensate (NSFC) to construct a road [194]. The other SP of different chemical families that appeared since 1930 are lignosulfonates, polymelamine sulfonates, vinyl copolymers, polyethylene oxide phosphonates (PEG). The development of the new generation of SPs replaced the older SPs in many applications [195]. Compared to poly-carboxylate and poly naphthalene-based SPs, lignosulfonates-based SPs have a longer workable time and initial setting time [196].

High-range water-reducing admixtures or SPs are critical ingredients in modern concrete to improve flowability at low water content. SPs are commonly used in high-performance, self-consolidating, fiber-reinforced concrete, and other applications [42]. SPs are surface-active agents that change the surface charges of cement particles to disperse them into smaller agglomerates. The formation of such cement clusters during the initial mixing of Portland cement with water is due to relatively large Van der Waals forces of attraction, which work at inter-particle distances of 5 to 7 nanometres(nm). Plasticizers can overcome this force by exerting a strong repulsive force at the surface-liquid interface, allowing the trapped water to escape. The loosely entrapped water particles are associated with the clustered particles of the cement. This water is then used in the hydration process, thus decreasing the amount of water that is to be added additionally otherwise [43]. The entrapped water between the cement particles is released when the SP is present; as a result, the fluidity or workability of concrete increases [44].

As a consequence, the ability to maintain consistency and flow is enhanced. These chemical admixtures are active for a certain amount of time before their effect wears off, and the cement paste starts to stiffen [45]. Since the dispersion of cement particles is the primary activity of SP, it is critical to investigate and comprehend dispersion behavior.

The molecules of the SP get adsorbed on the surface of the hydrated cement matrix and create an electrostatic repulsive force that releases the entrapped water molecules from the agglomerated cement particles, thus avoiding flocculation [26][197] [198]. According [199], the anionic charge density of additives plays a significant role in their adsorption onto the binder surface; additives with high anionic charge density adsorbed strongly onto the surface binder compared to additives with low anionic charge density. [200], reported that the amount of C_3A and the formation of soluble alkali sulfates significantly influence the adsorption rate of SP. [201] said that the dispersal of the cement particles could be attributed to the formation of the highly negative zeta potential of the cement pastes by the SP.

It is essential to ascertain whether a particular SP is compatible with the cement before employing it in mass concrete works [202]. [203] cited a total loss of fluidity when Portland cement was replaced by blended cement, and the SP content increased from 0.5 to 3%. The paper also reported that when SP exhibits compatibility with a specific mix composition, it loses compatibility with the incorporation mineral admixture. By measuring the flow time of the paste, the cement–SP compatibility can be investigated.

2.3.1 The Marsh Cone Test

The Marsh cone test is used to resolve the comparative fluidity of pastes with the presence of SP. It helps to understand the fluidity of the cement paste by calculating the time taken for the discharge of a specified amount of paste through a small opening of a cone, with the longer time required signifies lesser fluidity [204]. The type of admixtures, their content, and the dosage of SP influence the Marsh cone flow time [205]. The amount of time it takes for a paste to flow through the cone is proportional to its viscosity. The flow time increases as the viscosity increases, and so it becomes an index of the fluidity of paste [206]. When the flow time stops decreasing, or the dose of the SP reaches a point beyond which it has no fluidizing effect, the dosage of SP is said to get a saturation point [207] [208]. The shape of the Marsh cone flow time vs. SP dosage curve can provide a general understanding of the saturation point. A more quantitative description is possible by analyzing the slope of the curve [204].

According to [204], the cement-SP combinations that do not display a well-defined saturation point suggest an incompatible cement-SP relation. The saturation point can help determine the amount of SP to be added. The saturation level is the maximum for the specific type of cement, w/b ratio, and amount of admixture used. The above research also suggests that the cement paste should be considered to assess the saturation dose of SP rather than the mortar. This is because the sand content is not defined until the concrete has been optimized, and a priory assumption of the mortar composition would restrict the scope of the paste optimization to only fluidity.

The admixture dosage is measured as a weight-to-weight ratio between the solid substance and the cement [204]. Concrete is a non-Newtonian fluid with rheological properties that can be represented by the Bingham model [209]. According to [210], the Marsh cone accuracy rapidly diminishes beyond a plastic yield of 20 Pa. The cement paste is considered Newtonian fluid in the Marsh cone test, which is never ideally accurate. Bingham Model [203], [204] suggested that the addition of superplasticizer decreases the yield shears stress by keeping the plastic viscosity unaffected [203], [205], [206] The study found that when a large amount of PCE is added, the dynamic yield stress lowers, and the cement particles or agglomerates become more diffused, resulting in smaller agglomerates [211]. According to [212], a low dose of PCE resulted in a significant reduction of the yield stress of over 70%. Thus, it can be well estimated that the flow times obtained from the Marsh cone will have equivalent results as the yield shear stress, just like workability is determined using a slump test with Abram's cone's help [204]. Also, the rheology of the paste used in concrete differs from that synthesized independently [197][207][25]. This indicates that the ultimate development of the configuration should be done directly during tests conducted on concrete [202].

[213] observed that the Marsh cone has two limits. First, if the viscosity of the tested fluid is too low, there is no linear relationship between viscosity and flow time. Second, if the pressure gradient created by the fluid weight above the nozzle is insufficient for the shear stress to overcome the yield stress of the tested fluid in the nozzle, the flow may not occur.

2.4 LITERATURE REVIEW ON MODELLING

Concrete is a prevalent man-made building material on earth. With its unique properties of strength, modularity, durability and low maintenance, concrete is widely utilized as a construction material for roads, airfields, bridges, buildings, and dams throughout the world. [214], [215]. Specifications from the Bureau of Indian Standards (BIS) (IS: 456 2000)[216] govern the acceptance and rejection of any grade of concrete for the aforementioned structures in India. Among several properties of concrete, Compressive strength (CS) is one of the main properties of concrete that investigates the direct effect on the performance characteristics of a structure and ensures the quality of the final product [134].

In general, a normal concrete gains almost 85-95% CS within a time period of 28 days [217]. Therefore, designer and engineers always rely upon the 28-days CS and consider it as base for design and evaluation purposes. Accomplishing 28-days CS in the laboratory, either from the cubic or cylindrical specimens, is a multistage process, requires considerable quantity of materials (such as cement, fine/coarse aggregate) and almost one month for completion. It becomes more rigorous and time-consuming to test all constituent materials and conduct numerous design mix trials. All of these procedures not only extend the duration of the project but also increase its final cost.

In the past years, significant efforts have been made by several researchers worldwide to develop a generalized model for predicting the CS of different types of concrete. CS is a complex function and showing the non-linear relationship with other properties of concrete mix. Over a period of time, model developed through single linear and multiple linear regression [19], [218] lose their generalization ability for different boundary conditions. Therefore, relying on regression analysis to develop a prediction model for concrete CS is not feasible [219], [220].

In the recent years, Machine Learning (ML) has become more popular for solving the most complex problems of civil engineering due to its superior predictive ability as compared to conventional statistical techniques. Several researchers have adopted numerous ML algorithms, the very first fame was earned by [221] through Artificial Neural Network (ANN) technique in developing the prediction model for CS of high performance concrete (HPC). [222] found the least accuracy in predicting the CS of concrete using neural expert system technique. [223] observed the potential use of ANN in predicting the CS and slump value of High Strength Concrete (HSC). [224] revealed that ANN is significantly more effective than Genetic Operation Tree (GOT). [225] obtained satisfactory results in predicting the CS of HPC and Self-Compacting Concrete

(SCC) through ANN. [226] obtained highest accuracy for ANN and Multiple Additive Regression Tree (MART) followed by Support Vector Machine (SVM), Bagging Regression Tree (BRT) and Multiple Linear Regression (MLR). They also tried to validate the model using K-Fold Cross Validation (CV) technique. [218] used least quantity of dataset in developing the ANN model for predicting the CS of concrete prepared from blast furnace slag and fly ash. [227] combined ANN with discrete wavelet gradient boosted, gradient boosted, wavelet bagged, bagged algorithm. The accuracy measured in terms of R2 for each of the combination was more than 0.90 and the maximum was achieved for wavelet gradient boosted ANN. [228], [229] established that ANN and adaptive neuro-fuzzy inference system (ANFIS) algorithm optimized with Grey Wolf Optimizer (GWO) are sufficient in predicting the CS of normal, silica fume and HPC concrete. [230] [231] found ANN potential in predicting the CS of concrete prepared from Reclaimed Asphalt Pavement (RAP) and Rice Husk Ask (RHA).[232], [233] achieved remarkable performance of Extreme Learning Machines (ELM) and Multivariate Adaptive Regression Splines with Water Cycle Algorithm (MARS-WCA), respectively, in comparison to other ML algorithms in predicting the CS of foamed concrete. [234] obtained higher accuracy for ELM approach as compared to ANN in predicting the CS of concrete. [235] found that Modified Firefly Algorithm-Artificial Neural Network (MFA-ANN) model is sufficient in predicting the CS of HPC. [214] developed adaptive boosting model for CS of HPC, furthermore, tried to establish the generalization capability of model through K-Fold and literature published dataset. [236] employed ANN, ANFIS, ELM, ELM with GWO (ELM-GWO), Support Vector Regression (SVR) with radial basis function (RBF) kernel (SVR-RBF), and another SVR with a polynomial function (Poly) kernel (SVR-Poly) to predict the CS of concrete with blast furnace slag and fly ash. They concluded that ELM model with GWO can efficiently improve the accuracy of the model. [231] observed that ML techniques can efficiently be used for predicting the CS of geopolymer concrete with high level of accuracy.

2.5 CONCLUSION

When compared to control concrete, the majority of mineral admixtures enhanced the mechanical and durability characteristics of mortar and concrete. In some of these mineral admixtures, the improvement in the characteristics of concrete at later ages of curing was more significant than at earlier ages of curing. It was brought on by their passive behavior. Despite having a higher specific surface area than the others, the particles of these types of mineral admixtures were found to be coarser than the others (which is generally associated with the finer particles). It demonstrates how permeable these particles are. While mixing, these kinds of particles frequently absorb some water into their pores. The water absorbed by the pores is released back during following days as the amount of water in the hydrated cement paste drops, allowing the pozzolanic reaction to continue and increasing the qualities of the concrete as it ages. In a nutshell, the packing impact of inert SCM particles is more effective on the characteristics of concrete early on, but the pozzolanic action of SCMs is more effective afterwards. Mineral admixtures' impact on the characteristics of mortar or concrete are typically governed by four primary factors: (1) acceleration of cement hydration; (2) filler effect; (3) dilution effect; and (4) pozzolanic action.

The mechanical and durability characteristics of mortar and concrete are significantly influenced by the SCM's fineness of particle size. These SCMs' nucleation site action causes an increase in cement hydration. They provide more nucleation sites for the precipitation of hydration products because their finer particle size divides larger holes into smaller pores. It lessens the permeability of the mortar or concrete and increases the density of the pore structure. The filler action of various SCMs also increases the packing density of the mortar or concrete. Their particles bridge the spaces left by the cement's relatively coarser particles. The w/b ratio at the ITZ around the aggregate is likewise reduced by these smaller particles, bringing it into line with the rest of the hardened cement paste. Numerous studies found that when the proportion of mineral additive in concrete increased, many characteristics gradually improved. The mechanical and durability qualities of the admixed mortar/concrete, however, continued to deteriorate with further replacement after the optimal amount of cement substitution by SCMs due to their diluting impact. A diluting effect is another name for the substitution of cement. C3A content (which is related to cement content) and the production of $Ca(OH)_2$ decrease as there is an increase in the quantity of cement replacement by various SCMs. The pozzolanic activity of mineral admixtures is affected by the decrease in $Ca(OH)_2$ content. C3S and C2S react with water to create C-S-H and $Ca(OH)_2$ during the hydration of cement. Concrete's strength is improved by C-S-H, which causes the permeability to be reduced as a result. Because $Ca(OH)_2$ is very soluble in water, coming into contact with it increases the porosity of concrete. When SCMs are employed in conjunction with cement, $Ca(OH)_2$ is consumed due to their pozzolanic action, which causes secondary C-S-H gel to form when SiO_2 and calcium hydroxide combine. The secondary C-S-H gel causes a denser microstructure to form in the concrete.

The use of polycarboxylate (PC) superplasticizers (SPs) in cement-based materials has been shown to enhance their workability and reduce water content, leading to improved strength and durability. The effectiveness of SPs depends on their chemical structure and compatibility with the cement mix composition. The dispersion behavior of cement particles and the adsorption rate of SPs onto the surface of the hydrated cement matrix are critical factors that determine the performance of SPs in concrete.

Despite the extensive research on SPs, there is still a need for further investigation into their long-term durability, particularly in aggressive environments such as seawater, acidic or alkaline soils. Additionally, the optimization of SPs dosage and the development of eco-friendly and sustainable SPs could be an area of future research.

Based on the literature review presented, it appears that researchers have used a variety of ML techniques to predict the compressive strength of concrete. However, there are some concerns regarding the division of the dataset into training and testing sets, as well as the tuning of hyperparameters.

Many studies have used a random approach for dividing the dataset, which may lead to over-fitting or under-fitting of the model. Only a few studies have used other methods, such as stratified sampling. Additionally, many researchers have manually tuned hyperparameters, which can be time-consuming and impractical for high-dimensional datasets. Some studies have used automated approaches for hyperparameter tuning, but this is not yet common practice.

Furthermore, only a few studies have performed a validation process, and even fewer have used K-Fold CV or validated their models on external datasets. This raises questions about the generalizability of the models to new data.

Finally, while researchers have provided the hyperparameters values used in their models, the accompanying algorithms and their hyperparameters are often not accessible to non-researchers. This limits the practical applicability of the models for site and laboratory engineers who may need to quickly estimate the compressive strength of concrete.

The replacement percentage of mineral admixture was decided on literature review [237] [238] [239][164][240] [241][242]. Based on the findings of several studies in this field, a 30% replacement of cement with FA was considered [237]. According to Indian Standard, the percentage of fly ash in PPC should be between 15 and 35%[238].

Literature studies showed that the MS dosage between 7.5 and 12.5% had considerably improved the properties of the concrete [239][164][240], and the MS dosage considered in this study was 10%. The commercially available sulphate-resistant cement contains 40-60% GGBS. Many investigations have observed that GGBS up to 50% has greatly enhanced the properties of concrete [241][242]. Thus, the replacement of GGBS used in this study was 50%.