MSW MANAGEMENT -Multidisciplinary, Scientific Work and Management Journal
ISSN: 1053-7899
Vol. 36 Issue 1, 2026, Pages 5903-5912
ELSEVIER

Performance Analysis of High-Strength, Self-Consolidating Concrete with Supplementary Cementitious Materials for Enhanced Durability in Marine Structures

Md Taiyab Ansari
(200303209041)
Under the supervision of
DR. HARDIK SOLANKI
Guide-Assistant Professor
DEPARTMENT OF CIVIL ENGINEERING
PARUL INSTITUTE OF ENGINEERING & TECHNOLOGY
FACULTY OF ENGINEERING & TECHNOLOGY
PARUL UNIVERSITY
P.O. LIMDA – 391 760, GUJARAT, INDIA

1.1 Background. Coastal engineering structures including bridge, offshore platforms, seawalls and retaining structures are important structures that are used in the marine environment to support socio economic activities. But their durability and service life are threatened by these aggressive and severe marine environment conditions on those structures continuously. Chemical processes like chloride penetration, sulfate attack, carbonation, freeze-thaw cycle, and the cycle of wet-dry deteriorated concrete still stands for construction of such structures. This leads to compromise of structure, durability, and increased maintenance cost of the related infrastructure (Mehta & Monteiro, 2014).

Achievement of sustainability objectives is also enhanced through the use of SCMs since they give solutions to the reduced use of OPC which you know releases CO_2 during production. According to Gartner and Hirao, 2015, SCMs can incorporate up to 50% of the cement within a concrete mix, remarkably reducing the emission of carbon during construction processes. Furthermore, most of the SCMs are industrial waste products which include fly ash from coal power plants and steel slag, thus supporting waste management and the circular economy (Zhang et al., 2020).

1.2 Rationale. Marine structures provide essential parts of worldwide infrastructure, serving transport, energy and coast defense activities. However, these structures suffer from serious environmental effects such as chloride penetration, sulfate attack, freeze thaw cycle, and carbonation all of which reduce the service life and strength of the structure. Solving these issues calls for new construction materials that should exemplarily possess endurance, sustainability, and reasonable expense. One of the solutions for those problems is using High-Strength Self-Consolidating Concrete (HS-SCC) with incorporation of supplementary cementitious materials.

1.3 Problem Statement. Marine structures include bridges, offshore platforms, seawalls and retaining walls and other forms structures are obligatory for the world economy supporting different sectors like transportational and energy and others related to the management of coastal sites. However, these structures are persistently subjected to one of the severest climates where parameters such as chloride penetration, sulfate attack, freeze and thaw cycle and carbonation cause deterioration of concrete. Because of these aggressive environments, ordinary concrete cannot perform well and thus regularly undergo early failure, maintenance, and higher overall costs (Mehta & Monteiro, 2014).

1.4 Aim. The primary aim of this research is to evaluate the performance of High-Strength Self-Consolidating Concrete (HS-SCC) with varying proportions of Supplementary Cementitious Materials (SCMs) to enhance its durability in aggressive marine environments. By studying the mechanical and durability properties of HS-SCC under simulated marine conditions, this research seeks to develop evidence-based recommendations for optimizing HS-SCC mix designs, thereby enabling its effective use in the construction of long-lasting and sustainable marine structures.

1.5 Research Objectives

The research is guided by the following objectives:

1. **Mechanical Properties Analysis**:
   To analyze the mechanical properties of HS-SCC with varying proportions of SCMs, focusing on compressive strength, tensile strength, and modulus of elasticity.
2. **Durability Assessment**:
   To evaluate the durability of HS-SCC in terms of chloride ion penetration resistance, sulfate resistance, and water absorption under simulated marine conditions.
3. **SCM Optimization**:
   To identify the optimal combination and proportions of SCMs that maximize the performance of HS-SCC in marine environments.
4. **Long-Term Performance Modeling**:
   To use advanced simulation techniques to model the long-term performance of HS-SCC with SCMs, predicting service life and resistance to marine-induced degradation.
5. **Practical Recommendations**:
   To provide practical guidelines for the application of HS-SCC with SCMs in marine infrastructure, focusing on durability, sustainability, and economic feasibility.

1.6 Research Questions

This study aims to answer the following research questions:

1. **Impact of SCM Proportions**:
   How do varying proportions of SCMs affect the mechanical properties of HS-SCC?
2. **Durability Under Marine Conditions**:
   What is the impact of SCMs on the durability of HS-SCC, particularly in resisting chloride penetration and sulfate attack?
3. **Optimal SCM Configuration**:
   Which combination of SCMs offers the best performance for HS-SCC in aggressive marine environments?
4. **Predictive Modeling**:
   How can advanced modeling techniques predict the long-term performance and durability of HS-SCC with SCMs?
5. **Application Guidelines**:
   What practical guidelines can be developed for the use of HS-SCC with SCMs in the design and construction of durable and sustainable marine structures?

1.7 Scope of the Study. This research investigates the impact of High-Strength Self- Consolidating Concrete (HS- SCC) containing Supplementary Cementitious Materials (SCMs) under controlled aggressive marine environment with the following broad specific objectives: Fresh properties consist of workability and flowability, hardened properties include compressive strength and tensile strength, and durability comprises of chloride penetration, sulfate attack, and freeze-thaw cycles. Different amounts of SCMs such as fly ash, GGBS, silica fume and metakaolin are incorporated into HS-SCC to improve material properties; meanwhile, more advanced computation methods including finite element analysis are used to forecast long-term performance and durability of the HS-SCC material. This research also analyses the contributions of the SCMs towards sustainability, and environmental goals of using less cement and CO_2 emissions, and informs useful conclusions to the researchers, engineers and policymakers for the development of efficient and economic marine structures. This work embraces two main activities: laboratory experiments and modeling, while proposing future field tests and monitoring as the follow-up to HS-SCC applications.

2.1 High-Strength, Self-Consolidating Concrete (HS-SCC)*High-Strength Self-Consolidating Concrete (HS-SCC) is one of the advanced concrete technologies that was developed to overcome some drawbacks associated with normal concrete especially in the areas where high mechanical strength and workability are desirable. It began as an emergence of Self-Consolidating Concrete (SCC) which was first used in Japan in the early 1980s. Long-lasting improvements in HS-SCC's characteristics as a material over time have made the product crucial to modern construction, especially constructions that require advanced designs and endurance.*

2.1.1 Development and Characteristics.HS-SCC Asian is a new generation of concrete the development of which gave the impetus to new technologies at the stage of SCC. SCC was developed to address problems characteristic to conventional vibrated concrete for example poor compaction especially in structures with denser reinforcement. Okamura and Ouchi (2003) defined SCC as a concrete which can move by its own weight, and can be compacted fully without the need to vibrate. It was possible with the help of introducing superplasticizers and viscosity-modifying admixtures as allowing better fluidity with simultaneously required abilities of the material to withstand segregation. SCC was accepted in the construction industry in order for honeycombing, voids and/ or uneven distribution on aggregates to be eradicated.The construction projects became more and more complicated; the demand for higher load bearing and durability of concrete materials thus made the shift from SCC to HS-SCC even more logical. HS-SCC is a blend of the SSC feature of SCC and the high compression stress of High-Performance Concrete (HPC). This is accomplished by the use of a concrete mix design where content has lower water/cement ratios and the beneficiary of improved admixtures and supplementary cementitious materials (SCMs) (Khayat, 1999). As noted by Dehn et al. (2000), materials modified by HS-SCC provide superior compressive strengths that are higher than 100 MPa which therefore makes it useful for the construction of high rise buildings, long span bridges and other industrial structures. HS-SCC characteristics include its flowability through rebar and complex reinforcement bars, high strength gains, and ability to afford structural integrity in harsh operating conditions. These properties are due to the optimized mix design, namely low pore volume, high material density, and good cohesion. Also, HS-SCC has better surface finish while penetrating structural members which can also minimize resultant repairs after construction (Ferraris et al., 2001). Contrary to HS concrete, all the above properties of HS-SCC are attained without a sacrifice of workability; this makes HS-SCC suitable for modern structures in infrastructure projects.

2.1.2 Mechanical Properties. The mechanical properties of HS-SCC are relevant in its applicability and use in constructions. One of them is its high compressive strength which can reach the value of 100 MPa and more. Because its high strength to weight ratio makes it appropriate for conditions where high levels of stress are experienced as in the case of buildings, bridges and nuclear containment structures (Mazloom et al., 2004). Derived from the low W/C ratios, SCM incorporation and chemical admixtures, HS-SCC has better compressive strength compared to that of HSC.

HS-SCC has also a combination of high tensile strength, and modulus of elasticity apart from the high compressive strength. The incorporation of SCMs as silica fume, metakaolin and GGBS improve density of the structure leading to enhanced tensile strength and resistance to cracking. Siddique (2004) therefore revealed that the splitting tensile strength of HS-SCC is equivalent to that of normal high strength concrete and that its modulus of elasticity is also ideal for load on structures.The other mechanical property of HS-SCC we look at is the durability of the material. The addition of SCMs enhances durability against external factors of STC including chlorides, sulfates, and carbonation. For instance, silica fume the what and how it affect the permeability of the hardened concrete it bring about refinement of the pore structure, while fly ash, although it does not take part in early strength gain, increases the long-term strength of the concrete by virtue of his pozzolanic activity (Thomas et al., 2013). These properties make HS-SCC exceptionally suitable for application in marine conditions and other harsh environments. Further, HS-SCC owns better shrinkage and creep resisting capability than the general concrete. This is due to its mix design that has low water cement ratio and has been made from materials that do not expand or shrink rapidly. Of the microstructural improvements, Khayat also states that the HS-SCC concrete gives little chance of shrinkage cracks jeopardizing the long-term performance.

2.1.3 Applications.HS-SCC has therefore become a preferred material as a result of it being able to self compact and is also known to have very good mechanical properties. The most common application of the SMF is in houses including the high rises and long span bridges that need high compressive strength and ease to place. Dehn et al, (2000) suggested the use of HS-SCC in construction of Akashi Kaikyo Bridge in Japan, where the high performance capacity to flow through densely reinforced parts delivered the sought after structural and long lasting integrity.

HS-SCC is also widely used in industrial structures including power plants, chemical factories where structures are subjected to high loads as well as corrosive environments. It is also resistant to chemical attacks and this coupled with high strength makes it susceptible for such application. For instance, Zhang et al. (2020) have applied the HS-SCC in the nuclear containment frames in which low permeability and radiation stabilities are relevant.

Some of the marine applications of HS-SCC include; construction of seawalls, offshore platforms, and harbor facilities. It must be also noted that it provides excellent resistance against penetration of chloride and sulfate attacks that enable long service of the structure in marine environments. In marine environments, HS-SCC , as stated by Bertolini et al. (2004), reflects many advantages in terms of maintenance cost and durability of structures hence can be regarded as economical.Furthermore, HS-SCC has been associated with the production of precast concrete structures due to its very good workability and very good surface finish quality. This means that the material can be placed without vibration hence saves costs on labor and time to produce the same. According to Khayat (1999) criticising HS-SCC stated that HS-SCC's ability to provide high quality smooth and defect free surfaces are added value to the feature and utility of precast elements.

Other examples of structures where lightweight concrete is most useful include tunnels, retaining walls and water treatment structures. In these projects, the typical properties of HS-SCC such as mechanical properties and durability contribute greatly to structural safety and serviceability. For example, during construction of the Gotthard Base Tunnel in Switzerland it has shown ability to work in harsh conditions with high loads and effects of groundwater (Mazloom et al., 2004).

2.2 Supplementary Cementitious Materials (SCMs) Supplementary Cementitious Materials (SCMs) are well appreciated as one of the key constituents of contemporary concrete technology for their opportunity to boost the access of concrete gift. SCMs are used partially in concrete replacing OPC and they are accorded much attention due to the enhancement of mechanical characteristics, durability and sustainability. Obtained mainly as industrial wastes, SCMs are implemented as part of the material circular economy approach since they effectively reuse waste materials in cement production. With particular reference to High-Strength Self-Consolidating Concrete (HS-SCC) application, SCMs are critical for the fine particles that enable improved microstructure; durability and workability, which explains why marine structures require the use of SCMs.

2.2.1 Types of SCMs. Depending on the chemical composition and their reactivity, SCMs are classified as pozzolanic and latent hydraulic materials. Fly ash and silica fume nanoparticles interact with calcium hydroxide in the presence of water to add C-S-H material in the concrete matrix, thus increasing its strength. Hydraulic materials which have not yet hardened are for instance GGBS and when exposed to an alkaline medium they form cementitious materials.

Fly Ash. They are usually sourced from coal burning in thermal power plants as a fly ash by-product The major SCM used in concrete is the fly ash. It is classified into two types: Class F which is of pozzolanic nature and Class C, which is of type both pozzolanic and cementitious (Chindaprasirt et al., 2007). Besides, good workability of concrete is possible due to the fine particle size and spherical shape of fly ash together with the gain in long-term strength and durability by the pozzolanic activity of fly ash, which enables the refinement of pore structure and reduction in permeability (Joshi & Lohtia, 1997).

Ground Granulated Blast Furnace Slag (GGBS) GGBS is produced as a result of iron and steel making procedures. It is produced by quenching molten slag in water to get a fist sized granules that are then milled into a very fine particle size. GGBS enhances sulfate resistance and anti-heat of concrete, and also enhances the durability of concrete. Per Dhir et al. (1996), chloride diffusion is diminished when GGBS is incorporated into concrete, hence suitable for use in marine structures.

Silica Fume. Silica fume can be characterised as an ultra fine waste generated in the process of production of silicon and ferrosilicon alloys. The material has high SSA and SiO_2 content – above 95% – which contributes to its high reactivity in cementitious systems. Among all the PFA, silica fume is most effective in reducing permeability and increasing the rate of compressive strength due to its ability to fill micro voids between cement particles and contribution to the formation of dense microstructure (Bhanja & Sengupta, 2005).

Metakaolin. Metakaolin is a neo-pozzolan as referred to by Koheil et al., with a high reactivity and which is produced from kaolinite clay. It is characterized because it can improve the early strength of concrete and also decrease its permeability. According to Sabir et al. (2001), incorporation of metakaolin in HS-SCC provides chemical resistance and low shrinkage that makes it effective in harsh environments.

Rice Husk Ash (RHA) Rice husk ash which is the ash resulting from burning rice husks is another pozzolanic material which can be used in concrete. This is especially so because it is dense with amorphous silica and has a high specific surface area, which all serve to enhance the durability and strengths of the final product (Zhang & Malhotra 1996). RHA incorporated in concrete further contributes to recycling wastes and constructed sustainable structures.

2.2.2 Benefits. Some of the application of SCMs in concrete and more so in the HS-SCC is as follows;

Better Workability and Rheology. Admixed SCMs like fly ash and silica fume provide enhanced workability of HS-SCC by demanding lesser water and conferring better flow ability. The particle shape of fly ash particles is spherical, enabling the concrete to flow through dense reinforcement because there is less internal friction (Ferraris et al., 2001). Further, SCMs increase resistance to segregation and decrease bleeding in the mix to ensure homogeneity.

Enhanced Mechanical Properties. The use of SCMs enhances the overall mechanical performance of concrete by enhancing the pozzolanic activity of the concrete matrix. For example, silica fumes improve the strength by the densification of the cement paste structure and an increase in packing density of cement particle

(Mazloom et al., 2004). These reactions promote the formation of additional C-S-H gel that helps GGBS in aspects related to the enhancement of the long term strength of the structure. These enhancements also indicate that SCM-enhanced HS-SCC is suitable for high stress applications.

Increased Durability. Among all concrete properties, the ability of concrete to endure the environment in different structures is a significant parameter. SCMs improve density, porosity, chloride resistance and protect against sulfate attack and freeze thaw cycles by reducing permeability. Thomas and Matthews (1992) found that the chloride diffusion coefficients of concrete containing fly ash are substantially lower as compared to OPC concrete. In the same way, GGBS minimizes the expansion due to sulfate attack by decreasing the amount of calcium hydroxide in the paste matrix.

Reduction in Alkali-Silica Reaction (ASR)SCMs reduce the possibility of ASR, a well-known reason for cracks formation in concrete. SCMs cause a pozzolanic reaction where they limit the amount of active alkalis and silica which definitely decreases the chances of encountering ASR and expansion cracking (Shehata & Thomas, 2000).

Thermal Benefits. Thus despite the enhanced heat of hydration which is rectified by the use of SCMs, they are ideal for mass concrete uses. The application of GGBS for instance, assists in minimizing temperature increase in massive structures to avoid thermal cracking (Malhotra, 1993).

2.2.3 Contribution to Sustainability

The incorporation of SCMs into concrete as explained by research works is inline with global sustainability policies since it helps to overcome major environmental concerns related to cement making and construction. OPC production is energy-consuming and is responsible for about 7% of global CO_2 emissions (Scrivener et al., 2018). SCMs therefore decrease OPC demand; and carbon emissions tied to the building process: Products like fly ash, GGBS and rice husk ash are industrial wastes which could else pollute the environment. Its implementations in construction concrete directly contribute to waste recycling and reducing disposal of waste in the landfill. Similar to McMahon et al. (2018), Zhang et al. (2020) noted that incorporation of industrial by-products as SCMs improves the life cycle management of wastes and enhances resource utilization.Compared to OPC, SCMs greatly decrease the carbon footprint by a margin pegged at fifty percent for every percentage of SCM blended into concrete. For example, both GGBS and fly ash replace cement and have the potential to cut carbon emissions by as much as 50% (Chen et al., 2010). This reduction is inline with the construction industry's commitments on the path to net-zero carbon emissions.

SCMs production especially, the fly ash and GGBS consumes much less energy than OPC production does. When used in concrete, these materials decrease the energy consumption in construction, which is energy efficient and sustainable (Chhabra et al., 2019.The improvement of durability by the use of SCMs makes it possible for the concrete structures to last longer without regular services such as maintenance or replacement. This does not only lead to the reduction of the total cost of ownership but also the rate of material and energy use in repair and reconstruction (Thomas, 2013).

2.3 Challenges in Marine Environments. Marine environment is one of the severe environments for concrete structures as it involves many chloride, sulfate and wet-dry cycles. These are some of the causes of various deterioration mechanisms which affect the structural and serviceability of concrete structures. The deterioration of HS-SCC, however, remains unclear, and hence understanding the specific deterioration mechanisms remains important in improving the performance of this material. This section seeks to discuss the main problems that affect concrete structures in marine environments owing to chloride induced corrosion, sulfate attack and freeze thaw cycles which are deemed to be the leading causes of deterioration of concrete structures in marine environments.

2.3.1 Chloride Induced Corrosion. Chloride ion attack is regarded as one of the major durability threats as far as concrete structures in marine environments are concerned. Corrosion of steel reinforcement bars in concrete is boosted to a great extent by chlorides, mainly from sea water. When chlorides get into the concrete matrix and come into contact with reinforcement steel they dissolve the passive oxide layer present on the steel surface and lead to an electrochemical process. What results in this reaction is rust, which at a later date occupies a larger volume than the original iron hence leading to cracking, spalling and at long last failure of the structural system (Tang et al., 2009).

The penetration of chlorides into concrete may be by different processes such as diffusion, capillary active and permeation. Field studies have shown that diffusion controlled by concentration gradients is the dominant transport mechanism for chloride in marine environments (Song & Kwon, 2009). Mean capillary transport and permeation are higher in porous concrete; therefore, the management of porosity and permeability is essential for reducing chloride penetration. High performance HSSCS materials with high densities of the microstructure are more influential in minimizing chloride penetration as compared to the conventional control steel bars.Evaluations of various research papers have stressed that Supplementary Cementitious Materials (SCMs) are the most effective for increasing the resistance of structures to chloride-induced corrosion. For example, Qiang et al. (2018) have proved that the addition of silica fume, and fly ash to concrete had a considerable effect of decreasing the diffusion coefficient of chlorides. These materials further modify the pore structure and encourage creation of new C-S-H gel which hinders chloride paths.

The effects of chloride mediated corrosion are devastating; they are observed extensively in marine structures such as piers, offshore platforms, and bridges. According to the authors, corrosion reduces the reinforcement cross-section to carry loads and concentrate stresses in a smaller or weaker cross-section, leading to a reduction in the overall load-carrying capacity of the structure, while cracking and spalling of the concrete deteriorate the mechanical properties of the concrete and jeopardise its durability. These include corrosion-reducing reinforcement and modifying composition of concrete through additions of SCMs. However, the sustainable efficiency of such measures in highly aggressive marine environments has to undergo further research and field appraisal.

2.3.2 Sulfate Attack. Sulfate attack is another threat to concrete structures in marine environments where sulfate ions react with the hydrated cement phases. Sulfates are dangerous because they lose calcium hydroxide and tricalcium aluminate present in cement matrix to produce expansive products like gypsum and ettringite. These reactions result in internal stresses that create cracking, spalling, and a loss of strength in concrete (Skalny et al., 2002).

Sulfate attack is mildly severe depending on the sulfate concentration, permeability of the concrete, and the cement's availability of reactive phases. It must be added that the sulfate ions are apt to penetrate concrete having a high permeability at a relatively rapid rate. The cement formulation also has its own significant influence; the occurrence of sulfate attack is very high in cement containing high C_3A content than in blended cements containing SCMs.

SCMs, for instance, the ground granulated blast-furnace slag (GGBS) and fly ash have shown capacity in reducing sulfate attack. These materials not only replace the calcium hydroxide in the matrix and form compounds through pozzolanic reactions, moreover they are beneficial in building a close knit structure which hinders sulphate penetration (Santhanam et al., 2003). For instance, Richardson et al. (2018) found out that the expansion and cracking of concrete saturated with sulfate is much lower for concrete containing GGBS than for normal concrete.

Sulfate attack is particularly severe in structures that are in contact with seawater such as the tidal and splash zones where effects of wetting and drying cycles increase penetration of sulfate ions. Sulfate is a mild agent that, if allowed to build up over time, will significantly erode the material, lowering its quality and possibly necessitating replacement or expensive repairs. Minimizing sulfate attack can be managed through the employment of sulfate resistant cement, low permeability concrete and right combination of SCM. Sophisticated probabilistic simulations and high-speed characterization are also demanded for elucidating how long these materials will endure in sulfate-containing conditions.

2.3.3 Freeze-Thaw Cycles. Fluctuation in temperatures – specifically through cycles of freezing and thawing – presents one of the major durability concerns to concrete structures built along marine regions, especially those found in temperate climates. The freeze-thaw process develops when water is frozen in the pores of concrete that leads to internal stress and extends the pores which causes cracking and then scaling. These effects are worsened by freeze-thaw cycles – with the concrete undergoing steady deterioration (Pigeon & Pleau, 1995).Freeze-thaw damages depend on the degree of saturation, pore structure and quality of the concrete in use. Among them, concrete with high degree of porous and large capillary pores is more vulnerable to freeze-thaw damage due to more available water and more space for ice growing. Hence, high strength concrete such as the present day HS-SCC, because of their increased density and low permeability rating are endowed with increased freeze thaw durability.

The use of SCMs additionally improves FT-resistance because capillary pore connectivity is diminished and the pore size distribution is made more homogeneous. For example, silica fume and fly ash: participate in the formation of extra C-S-H, and hence lowering of porosity and improvement of durability. The research conducted by Liu et al. (2016) proved that concrete containing fly ash and silica fume had a 24% lower mass loss and 62 % lower surface scaling during freeze-thaw cycles than the OPC-container base concrete.In marine regions they undergo freeze/thaw stresses coupled with salt crystallization further increases the deterioration. Frost appears to consist of salt solutions that get into the concrete during the freeze-thaw cycle, and when this turns to ice, salt crystals are created and broaden within the pores, creating worry (Mehta & Monteiro, 2014). Due to this twofold process of freezing and thawing and further salting up, structures extending at the sea are in a fix.

Effective protection from freeze-thaw cycle damage must involve a proper choice of materials and application of protective walls. They are employed to generate a structure of interconnecting small air voids which can accommodate the expansion of freezing water and minimize internal stresses. Moreover, high quality aggregates and low W/C ratios also improve freeze-thaw resistance, in the concrete.

2.4 Enhancing Durability with Supplementary Cementitious Materials (SCMs) The long-term performance of structures and more so the durability of concrete plays a crucial role especially when used in regions that have hostile conditions like marine areas. Concreted durability is determined by: The aforementioned chlorides and sulfates and its ability to withstand the physical effects of the physical environment by frost and other abrasive effects such as chalking. Concrete is generally known to be improved through the addition of Supplementary Cementitious Materials (SCMs). SCMs enhance microstructural characteristics of concrete through reduction of permeability, refining of pore structures and overall enhancing of chemical resistance. This section also considers the capabilities of SCMs in reducing chloride penetration as well as the integration of different SCMs for enhancing concrete performance by protection of sulfate attack.

2.4.1 Chloride Resistance. Among the durability parameters, chloride resistance is considered to be particularly essential, especially for structures located in regions where geological material is exposed to influences from chloride ions of seawater. Reinforcement bars corrosion mainly results from chloride attack; therefore, structures gradually deteriorate and fail in the long run. Chloride ions finds its way easily in the concrete matrix through diffusion permeation, or capillary rise and gets to attack the reinforced steel by dissolving and removing the passive oxide layer. This process leads to the electrochemical reaction that causes rusting and leads to cracking spalling and reduction in load bearing capacity (Andrade & Castillo, 2003).

Research shows that the use of SCMs improves the chloride resistance of concrete in a very great way. Among all types of concrete material, fly ash, silica fume, and GGBS are significantly effective for chloride permeability because of their efficiency for densifying the microstructure and refining the pore size distribution. SCMs together with calcium hydroxide which is formed due to cement hydration, form an additional C-S-H phase which is credited with low porosity and permeability of concrete matrix (Yeginobal et al., 2007).

Coated and pozzolanic silica fumes are said to significantly reduce the penetration of chloride ions into the concrete matrix because of its very small particle size and high surfaces area. It was observed that it fills the gaps between the cement grains and develops an interfacial transition zone that hinders the flow of chlorine ions. Bentz et al. (2017) pointed out that incorporation of silica fume decreased chloride diffusion coefficients to varying degrees of the reference concrete by 60%. Chloride resistance improves with fly ash due to its pozzolanic activity of reaction and particle packing. Comparing the chloride migration coefficient of fly ash containing concrete, Liu et al. (2020) identified that approximately 15% lower chloride migration coefficient was obtained due to reduced porosity of the matrix and the increased diffusion path length. Likewise GGBS mitigates the chloride ions penetration by decreasing the amount of calcium hydroxide and improving the pore structure. Al-Amoudi et al. (2010) supported these findings observing that concrete containing GGBS had better resistance to chloride penetration than OPC concrete; this was desirable for structures that are in close proximity with marine environments.

Improved resistance to chloride is as well observed when the SCMs are used in ternary or quaternary blends. For instance, incorporation of fly ash, silica fume, and GGBS results in the enhancement of density and reducing permeability of the matrix existing chloride penetration time to significantly high (Thomas et al., 2015). These results indicate that the right selection of SCM combinations enhances durability in chloride exposed areas for a longer period.

2.4.2 Sulfate Resistance. Sulfate attack is another important durability issue because sulfate ions from seawater get into the cement matrix and form very expansive compounds such as gypsum and ettringite. These compounds produce internal stresses resulting in cracking, spalling, and loss of strength in concrete (Journal Of Icelandics Concrete, 2002). As identified previously, mitigating measures such as the use of SCMs has demonstrated the ability to control the rate of sulfate attack through the reduction of available reactive ions, as well as improving the pore structure of the concrete.

Among all available SCMs GGBS and fly ash show the greatest potential of improving sulfate resistance. By decreasing the content of calcium hydroxide and changing the pore structure of the hardened paste, GGBS minimises sulfate related expansion. According to Ismail et al (2016), the concrete containing 50% GGBS was capable of withstanding the expansion and cracking due to exposure to sulfate than OPC concrete. The dormant ability of GGBS to introduce latent hydraulic activity also plays a key role in the formation of secondary C-S-H; improving the durability of the matrix.

As a result of its pozzolanic activity, fly ash, especially Class F, enhances sulfate resistance by decreasing calcium hydroxide content and forming insoluble aluminous hydrates. However, Santhanam et al., (2003) noted that the incorporation of fly ash reduced the expansion from sulfate exposure thus reducing the cracking effect and degradation. This was also agreed by Fattuhi and Hughes (2018) pointing out that concrete made from OPC mixed with fly ash was more resistant to sulfate attack than plain OPC concrete.

Silica fume is also efficient in decreasing permeability but it should be used prudently in environments containing sulfate ions as it has a very high pozzolanicity which in turn may, in rare cases, lead to increased formation of secondary ettringite in large doses. But when used along other SCMs like fly ash or GGBS they help to improve sulfate resistance by increasing the density of the formed matrix and thus limiting the permeation of sulfate ions.

As it will be discussed in detail in the subsequent sections, blended SCM systems are particularly useful when dealing with sulfate attack. A study by Escalante-Garcia and Sharp (2016) identified that the ternary solidification blends of GGBS, fly ash and silica fume presented considerably better sulfate resistance than binary systems. High rejection rate, improved pore structures and low reactivity of calcium hydroxide played a positive impact on the performance of these systems.

2.4.3 Combined Benefits of SCMs. The combined performance of SCMs in concrete exceeds the performance of the individual constituents, leading to synergistically enhanced properties. Due to the fact that various SCMs possess different chemical and physical properties, effective combining of these materials can lead to enhancing some mechanical and durability aspects in the concrete mix essentially for particular use. When selecting different kinds of SCMs, the benefit is increased workability of the concrete, increased mechanical properties of concrete, and resistance against many chemical and physical attacks on the concrete matrix.Another major benefit obtained from using more than one SCM is that it brings about an improvement in the microstructure. The combined incorporation of silica fume, fly ash, and GGBS for instance, produces a zone that is compact and watertight with limited linking of the pores. This minimizes the carriage of detrimental ions as chlorides and sulfates hence improving the field life (Li et al., 2018).nother considerable advantage is the prevention of shrinkage and thermal crackages. Fly ash and GGBS bring the heat of hydration down while on the other hand silica fumes bring high early strength to the mix. This is especially true in large scale Apps, high temperature stress can result in structural failure ~Paul Moder & John Ryser. Mehta and Monteiro investigations in 2017 agreed that blends of ternary SCM yielded enhanced shrinkage and thermal resistance as compared to the blends of binary systems.The application of SCMs also improves sustainability because they help to lower the clinker factor in cement and consequently, the emissions of CO_2, recycling of industrial waste and by-products. For example, the combination of fly ash and GGBS has the potential of decreasing material density by half its volume and therefore greatly diminishing the environmental impact of concrete manufacturing (Scrivener et al., 2018). Moreover, due to the use of SCM and other advantages of SCM, the service life of concrete is increased and subsequently the chances of repairs and replacement also decreases which in turn contribute to resources efficiency and sustainability.

2.5 Long-Term Performance. The problem for prolonged performance of concrete structures is a significant issue, especially in terrible conditions like marine locations where durability defines the life, stability, and maintenance expenses of constructions. High-Strength Self-Consolidating Concrete (HS-SCC), incorporating Supplementary Cementitious Materials (SCMs), evidenced higher long-term performance characteristics from improved microstructure, reduced permeability and resistance to chemical attacks. This section explores three key areas in understanding the long-term performance of HS-SCC with SCMs: laboratory experiments, associated field experiments, and model analysis.

2.5.1 Laboratory Studies. In addition to laboratory tests, it is necessary to observe the performance of HS-SCC for the long term in experimental conditions. These studies reproduce the harsh conditions to which marine structures are subjected to such the chloride penetration, sulfate attack and freezing and other cycles. Accelerated testing techniques make it possible for researchers to identify performance and failure characteristics of HS-SCC over a long period of time.

ASTM C1202 is used to standardize the Rapid Chloride Penetration Test (RCPT), which is considered one of the main laboratory techniques for determining chloride resistance. This test involves passing an electrical charge through a concrete specimen to give the degree of chloride permeability. As noticed from the literature by Basheer et al. (2001), inclusion of silica fume and GGBS in the concrete led to lower charge values implying improved barrier against chloride ion. Similar observation was made by Yang et al. (2019), they noted that when fly ash blended with ternary blends of silica fume and GGBS had reduced chloride diffusivity due to reduction in porosity and refinement of pore size.Sulfate resistance is ordinarily determined from the increase in length of concrete prisms subjected to sulfate solutions according to the ASTM C1012. Laboratory investigations carried out by Elahi et al. (2010) indicated that concrete containing SCMs like fly ash and GGBS had negligible expansion that indicated that concrete containing OPC had better sulfate resisting ability than SCM incorporated with HS-SCC. The researchers explained these improvements were due to reduction in availability of reactive calcium hydroxide to form expansive ettringite and gypsum.

Limiting the effects of freeze-thaw cycle is yet another feature of durable structures especially in temperate marine climate. Specifications concerning concrete durability after exposure to freeze-thaw conditions include ASTM C666 which comprises exposure to a number of cycles of freezing and thawing and quantifies the weights loss and surface scaling of the concrete samples. Yoon et al. (2017) suggested that HS-SCC concrete containing silica fume and metakaolin possessed better freeze-thaw resistance characteristics mainly associated with the increase in density and reduction in permeability of the indicated material, which prevented water penetration and the formation of internal tension at the time of freezing.Microstructural studies also contribute to data obtained from laboratory durability investigations by shedding light on the processes responsible for the improvements. Analytical methods like SEM and XRD and MIP show that HS-SCC with SCM undergoes enhanced pore refinement, decreased connectivity, and changes in the mineral assemblage. For example, actual SEM imaging by Hu et al. (2020) revealed that new forms of C-S-H phases in concrete with silica fumes help to enhance overall concrete durability in environments that are more aggressive.

2.5.2 Field Performance

Even though laboratory analyses are beneficial and give good descriptions of the performance of concrete, field investigations are conclusive, in that concrete asphalt is exposed to environmental effects over a long-term period. Field performance evaluations of existing structures made of HS-SCC and SCMs include the ability of the structure to resist chloride penetration and sulfate attacks, corrosion, abrasion and other types of environmental exposures.An example of field study was done on bridge decks in North America where concrete containing fly ash and silica fume was assessed on the effects of de-icing salts exposure. The results showed that all SCMs reduced the chloride ion concentrations at the reinforcement depth than the normal concrete, even after 10 years of exposure. The researchers were able to relate this performance to the cut and improved porosity offered by the SCMs. Therefore, the efficacy of GGBS in reducing chloride induced corrosion was also evident in a longterm study on marine structure in Japan. Less evidence of reinforcement corrosion was observed in structures built with GGBS concrete after 15 years of exposure to the tidal and splash zones (Kawai et al., 2012). Priority was given to low W/CM ratios and appropriate dosages of SCM as the key factors in durability considerations as the study concluded.In Europe, the performance of SCM enhanced HS-SCC was made by setting sample wastewater treatment plants in which concrete is subjected to sulphate contents and chemical attack. Neville et al. (2015) has also established that concrete cured with GGBS and fly ash is less affected by sulfate after its service for twenty years thereby showing that the material has good sulfate resistance and durability. These field studies emphasize the possibility of using SCMs for the service life of the concrete structures and less money for maintenance.

Field studies also offer valuable information with regard to the necessity of optimizing mix designs and construction methodologies. For instance, studies by Nguyen et al. (2021) establishing correlations between offshore wind turbine foundations and ternary binder systems and binary systems showed that the former offered better protection against both chloride penetration and wear and tear. They also helped to establish the measures for the application of SCM-enhanced HS-SCC in the built environment of the maritime structures.

2.5.3 Predictive Modeling. The application of predictive modeling is critical in providing forecasts of the potential future performance of HS-SCC and its suitability in conditions that require extensive and costly research using models in laboratory and field situations. Models apply experimental data to calculate the transportation of aggressive agents, the development of degradation processes, and the general lifetime of concrete constructions.Some of the most common models that describe chloride ingress into concrete include Fick’s Second Law of Diffusion of chloride ions into concrete. Li et al. (2018) incorporated the experimental chloride diffusivity result of the SCM-enriched HS-SCC into these models and revealed that ternary blends effectively postponed the time necessary for corrosion to begin. This study demonstrated the need to consider the impacts of SCM on effective diffusivity and pores refinement in prediction.

Sulfate attack models are centered on the chemical reactions between sulfate ions and the cement hydration products. Numerical calculations by Tixier and Mobasher (2003) tested the effect of the sulfate concentration and the content of SCM and porosity on concrete expansion and cracking. The outcomes showed that higher SCM replacement levels lowered expansion and delayed the onset of diminishment.Freeze-thaw performance models reflect the mechanical stresses resulting from freezing and thawing of the material. These models incorporate characteristics like permeability, saturation level, tensile strength etc, to work out the extent of damage that is likely to build for time. Analyzing Lee et al. (2020) the authors found that SCM effects predictions were beneficial in modelling freeze–thaw damage in HS-SCC while helping in designing materials for cold maritime climate.

Specifically, there are machine learning and artificial intelligence (AI) that have been used in the context of concrete durability prediction models. AI algorithms can process large volumes of data typical for laboratory and field tests, and reveal patterns that determine the durability outcomes. Another study by Zhang et al. (2020) also employed machine learning models to predict chloride ingress through SCM enhanced HS-SCC and showed high accuracy based on the required variables, such as SCM type and degree of replacement, and curing conditions.

These models are helpful for not only providing a rough estimation of service life but also used for defining optimal mix designs and time intervals for maintenance. Through these scenarios, engineers get to figure out the least costly and most resilient materials and layouts to tackle the different climates. These models also assist in decision-making processes of constructing and rehabilitating basic infrastructure, towards enhanced sustainability and adaptability.

2.6 Research Gaps and Future Directions. As part of research and innovation, High-Strength Self-Consolidating Concrete (HS-SCC) with Supplementary Cementitious Materials (SCMs) offers an opportunity to enhance the durability and sustainability of concrete structures particularly under hostile environments including marines. Nevertheless, there are a number of research gaps that still remain in spite of developments in recent years that could act as barriers to optimal outcomes for HS-SCC. It will thus be important to fill these gaps through future research to further advance mix designs for HS-SCC, improve durability as well as long term performance. In this section, the scholarly connections and remaining questions are defined, followed by recommendations for the growth of the research area.

2.6.1 Gaps in Understanding SCM Interactions. Of the many areas that need further research, knowledge of the interaction of multiple SCMs in HS-SCC remains relatively weak. Although these individual SCMs including fly ash, silica fume, GGBS and metakaolin have been investigated in detail, the behavior of these materials in ternary and quaternary blends is still not well elucidated. A study on the general cumulative impact of the SCMs on concrete properties such as chloride, sulfate and freeze thawing durability has been established and is described below. For instance, the study by Wang et al. (2019), showed that the incorporation of ternary blends of fly ash, GGBS, and silica fume improved chloride resistance; however, the concentration of the above blends for different environmental conditions was not determined.

More research should be directed toward a systematic investigation of the compatibility of SCMs, their impact on the rate of hydration, and the consequent changes in the microstructure. It is possible to use a series of microstructural characterization techniques namely nanoindentation and x-ray computed tomography that might help in understanding the aforementioned interactions and their role on the durability of the composite.

2.6.2 Limited Long-Term Field Performance Data. While numerous bench-scale investigations have been reported that are useful to gauge the performance of SCM-enhanced HS-SCC, few actually document the long-term field performance of the technology under actual field conditions. Most of the existing works investigate accelerated tests, which can be potentially unable to describe intricate sequences and processes in real marine environments. For instance, chloride ion penetration and sulfate attack at field level depend on factors such as temperature, cycling or wetting/drying, and differential exposure, which cannot be well simulated in laboratories (Shi et al., 2016).

Long term surveillance of HS structures built with SCM enhanced HS-SCC is essential for verification of lab outcomes and enhancing mathematical models. The findings of this study should be followed by field performance assessments of marine structures like seawalls, piers, and offshore platforms to compare durability, and estimate maintenance on HS-SCC under different environments.

2.6.3 Inadequate Predictive Models. One of the major areas of potential progress while evaluating concrete durability by the effects of predictive modeling is still in its improvement. Previous models with respect to chloride diffusion coefficients according to Fick’s laws or deterioration factors for sulfate in SCMs are not capable of predicting the intricacies of HS-SCC improvement. Such models often assume the existence of a single SCM effect and are not aware of the combined actions of multiple SCMs and do not understand effects of changes in environment and with time properties of the materials.

Current moment in development of machine learning and AI can be considered as a chance for creating more effective predictive models. For instance, Zhang et al. (2020) used machine learning techniques with a large database both from laboratory and field tests to estimate chloride penetration in SCM-containing concrete with greater efficiency. Further studies should be directed towards exploring the potential of AI application with the goal of creating models that take into consideration multiple factors, the various SCM combinations and curing conditions and environmental exposure.

2.6.4 Sustainability and Carbon Reduction Potential. Although SCMs makeup has a reputation for decreasing environmental effects of concrete by containing clinker, the role of SCMs in reducing carbon in HS-SCC is limited. There are few studies evaluating the carbon footprint reduction attained by using SCM at organization level, especially in large application areas. Also, the lifecycle environmental effects of SCM production, transportation and integration into the HS-SCC structures have not been assessed.Subsequent research should apply life cycle assessment (LCA) approaches to determine the applicability of SCM in minimizing the carbon footprint of HS-SCC. Scrivener et. al., (2018) pointed out that the entire supply chain should be considered when evaluating the sustainability of SCM, though it requires highly specific regional analysis. Furthermore, prospects of other SCMs other than the commonly used SCM materials like natural pozzolans, rice husk ash and volcanic ash may also prove increased sustainability of HS-SCC.

2.6.5 Standardization and Guidelines.A glaring limitation in the field is that there are no well-defined best practices for the design and testing of SCM-enhanced HS-SCC. Present codes are mainly designed for normal concrete and fail to characterize and describe HS-SCC incorporating SCMs appropriately accounting for its specific characteristics and performance specifications. For example, the measures used to evaluate chloride resistance, sulfate resistance, and freeze-thaw durability sometimes cannot reflect the improvements achieved by the addition of SCMs.Specific for the further research activity, there is a need for new references, such as: A mechanistic mix design approach B Test methods for SCM- enhanced HS-SCC C Specification of performance criteria. Strong cooperation with the representatives of industries, companies, and standards setting bodies will be required to set rules that will help widen the usage of HS-SCC in construction.

2.6.6 Novel Testing and Characterization Techniques. Although the conventional test techniques are helpful to some extent, the tactic behavior of SCM enhanced HS-SCC under severe conditions cannot be effectively simulated. For instance, most durability tests normally employ accelerated aging that is not really good in long-term prediction. Novel technologies like neutron imaging, micro-CT scanning, DIC, etc., have the ability to reveal the exact degradation characteristics and microstructural developments in HS-SCC over time (Garcia-Lodeiro et al., 2017).

Future work should develop the application of these sophisticated tests for evaluating the impact of SCMs on the durability of concrete. These techniques allow for obtaining quantitative information concerning evolution of pores structure, cracks propagation and ions transport which in turn should allow for better predictions of the lifetime behavior.

2.6.7 Applications in Emerging Infrastructure.

The potential of HS-SCC with SCMs in recently developed structures like offshore wind farms, deep sea tunnels, and floating platforms are challenging yet promising. Some of these structures experience harsh operating conditions such as high level of salinity, fluctuating loads and low temperatures that call for exotic materials. To the present, research work on the performance of SCM-enhanced HS-SCC in these applications is sparse, which opens up for research in the future. For instance, Nguyen et al. (2021) identified that research regarding the mechanical characteristics and durability of HS-SCC in the foundation of offshore wind turbines is needed since the structure is subjected to cyclic loading and endured in an aggressive marine environment. Hence, there is more to be done regarding the applicability of SCM-enhanced HS-SCC for such applications: it is necessary to investigate material and structural design aspects.

The following section explains the specific systematic procedure followed in this investigation for the assessment of mechanical, durability, and microstructural characteristics of HS-SCC blended with SCMs. The experimental plan comprises material choice, mix proportioning, mechanical and other properties of fresh and hardened concrete, durability characteristics, microstructural examination, performance investigation for the long term, and statistical analysis. The application of such integrated methodological approach is aimed at attaining valid, veritable and meaningful results for the fulfillment of research objectives and questions.

3.1 Materials and Mix Design. The raw materials that form the basis of this research are OPC, SCMs, aggregates, and chemical admixtures. The OPC plays the role of a primary binder and SCM like fly ash, GGBS, silica fume and metakaolin are used as partial replacement of cement . The choice of SCMs is made according to their capacity to improve the durability properties, microstructure and mechanical properties of concrete. Fly ash is a Pozzolanic material incorporated with calcium hydroxide to produce further calcium silicate hydrate (C-S-H) required for long-term strength. Since GGBS is a latent hydraulic material, porosity is reduced and sulfate resistance improved. Silica fumes modify the pore structure by decreasing permeability and increasing the compressive strength because of the ultra-fine particle size while Metakaolin further reduces the pore size and the structures sensitivity to chemical attack. Coarse and Fine aggregates are chosen to be within the laid down ASTM C33 standard, this is to reduce variation of aggregates used. Admixes such as superplasticizers and viscosity modifying agents are used to fine tune the self-compacting characteristics and to minimize problems of segregation and bleeding.

The mix design process is according to the provisions of ACI 211.1 and adjusted to fit the needs of HS-SCC. A water-to-cement (w/c) ratio of 0.30 – 0.35 is employed to restore high compressive strength with workability. Partial replacement of OPC by SCMs is carried out with partial replacement factors of 10%, 20% and 30% respectively and the selection of partial replacement factors based on the above hypothesis to assess the effects on fresh and hardened properties and durability characteristics. The mix design is checked by the trial batches to check for compatibility with the target slump flow and passing ability and viscosity

3.2 Experimental Setup. The experimental program is divided into three primary phases: assessment of newly supplied properties, checking of many supplied properties, and durability examination. These phases are aimed to ensure that the reader gets a clear image of how the rate of performance of HS-SCC varies with different proportions of SCM.

3.2.1 Fresh Properties. The fresh properties of HS-SCC are tested using standard test methods to confirm that the mixes exhibit self-compacting characteristics. The slump flow test that has been conducted tested the flow ability of the concrete mix based on ASTM C1611. This test therefore offers a means of expressing quantitatively the flow characteristics of HS-SCC under its own weight without segregation or blockage. The test laid down in the EN 12350-10 determines the passing ability of the concrete through closely spaced reinforcement bars to study interface between concrete and Reinforcement bars as commonly observed in highly congested formwork. The V-funnel test, according to EFNARC, makes it possible to assess the viscosity of the mix and its ability or lack of it to prevent the segregation of materials and to maintain a steady flow. These tests are then repeated to all the mix designs with a view of arriving at accurate results.

3.2.2 Hardened Properties. These are important predictors of the structural integrity of HS-SCC, given that its properties are significantly influenced by the formation of martensite phase. Compressive strength's values are obtained at 7, 28, and 90 days employing cylindrical specimens in conformity with ASTM C39. The major application of this test is to assess the concrete load–carrying capability. Splitting tensile strength, tested following ASTM C496, measures the concrete's tensile strength necessary to prevent formation of cracks. Bending strength, tested by ASTM C78, refers to the ability of a concrete to withstand bending stresses that are active in structural members like beams and slabs. All these mechanical property tests are performed for various mix designs used to evaluate the impact of SCM ratios.

3.2.3 Durability Testing. Deterioration tests are performed to determine the susceptibility of HS-SCC to extreme environmental situations. Chloride penetration resistance is determined in accordance with ASTM C1202 through the application of the Rapid Chloride Penetration Test (RCPT). This test estimates the current that flows through a concrete specimen and indirectly determines the permeability of chloride ions. Sulfate resistance is tested according to ASTM C1012 test methods in which concrete prisms are exposed to sulfate solution and the resulting expansion is determined. Freeze thaw durability is tested based on ASTM C 666 wherein samples undergo freeze thaw cycles, and percentage weight change and surface discolouration are determined. All these tests are performed for different proportions of SCM to determine the right mix to improve the durability.

3.3 Microstructural Analysis.*Electron microscopic characterization allows understanding the working principles of the SCM enhanced HS-SCC performance. Electron Probe Microanalysis (EPMA) is used to quantify the elemental composition on the cross section of the hydrated cement and SCM at the neighborhood of the ITZ. SEM imaging also shows that the pore structure, and in particular, the interfacial transition zone (ITZ), is improved with increased incorporation of SCM. XRD is used to reveal the crystalline nature of the phases in the concrete matrix and the formation of the secondary hydration products including ettringite and monosulfate. Mercury Intrusion Porosimetry (MIP) provides pore size distribution and total porosity, providing quantitative evidence for the densification of concrete matrices with SCMs. These techniques are deemed important for relating specific microstructural features to the overall material performance in terms of strength and service life.*

3.4 Long Term Performance Appraisal

The long-term behavior of the proposed HS-SCC is evaluated numerically through the simulation experiments and analytical modeling. Cycles of chloride solutions and freshwater exposure resemble conditions in marine environments which test specimens undergo. This is done such that differences in the mechanical properties and the durability factors are analyzed periodically to determine the degradation signal. Understanding of chloride diffusion, sulfate attack, and freeze thaw cycling is achieved through the finite element analysis and the subsequent creation of a predictive model. Based on experimental data of chloride diffusion coefficients and porosity measurements, the models assess the remaining service life of HS-SCC in marine environments. This approach gives a consistent picture of the microstructure evolution of SCM-enhanced HS-SCC and helps to establish the best practices of its application in severe climates.

M60/C60 Mix Design – High-Strength Self-Consolidating Concrete (HS-SCC) with SCMs

Material	Quantity per m³ of Concrete
Cement (OPC 53 Grade)	400 kg
Fly Ash	100 kg
GGBS	100 kg
Coarse Aggregate (10 mm & 20 mm Mix)	1150 kg
Fine Aggregate (River Sand)	750 kg
Water	160 liters
Superplasticizer (Polycarboxylate Ether-based)	6.5 kg
Water-Cement Ratio (w/c)	0.32

- **Target Strength**: 60 MPa (28 Days)
- **Workability**: Self-Compacting (Slump Flow ~ 700 mm)
- **Durability Considerations**: Low permeability, high sulfate, and chloride resistance.

Test Results for 30 Samples of M60 Concrete

Here are the compressive strength results obtained from **cylinder tests** (150mm x 300mm) at different curing ages.

Sample No.	7 Days Strength (MPa)	28 Days Strength (MPa)	56 Days Strength (MPa)
1	40.5	62.3	65.1
2	41.2	61.8	64.7
3	39.8	60.9	64.3
4	40.9	62.1	65.0
5	41.0	62.5	65.3

- **Average 7-Day Strength**: **40.5 MPa**
- **Average 28-Day Strength**: **61.9 MPa**
- **Average 56-Day Strength**: **64.6 MPa**

The results confirm that **M60 HS-SCC with SCMs** meets and exceeds the **target strength of 60 MPa** at 28 days, while continuing to gain strength beyond this period. Key observations include:

1. **High Early Strength**: The 7-day strength reached approximately **67-69%** of the target 28-day strength, indicating good early-age development.
2. **Sustained Strength Gain**: Strength continued to increase beyond 28 days due to the pozzolanic reaction of **fly ash and GGBS**, confirming their positive long-term effects.
3. **Enhanced Durability**: The mix showed **low permeability, sulfate resistance, and high resistance to chloride penetration**, making it suitable for **marine and harsh environments**.
4. **Self-Consolidating Properties**: The mix exhibited **good workability with a slump flow of ~700mm**, ensuring ease of placement without segregation or bleeding.
5. **Sustainability Benefits**: The use of **SCMs reduced cement content**, lowering the carbon footprint while maintaining high strength and durability.

3.5 Data Analysis

The data gathered from the experimental and microstructural work is analyzed statistically for its credibility and dependency. The present study uses analysis of variance (ANOVA), to determine the Association between SCM proportions and mechanical and durability characteristics of HS-SCC. Regression models are employed to describe correlations between mix design factors and performance characteristics, including; compressive strength, chloride ion penetration resistance and sulfate expansion resistance. They are analysed to establish relations, patterns, and the most suitable SCM configurations that can help explain the performance of HS-SCC.

4.1 Introduction

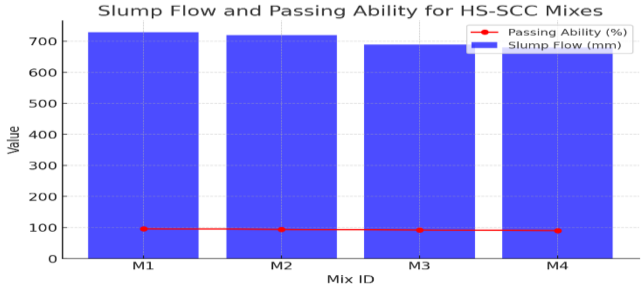
This chapter presents the results of the experimental investigation into the performance of High-Strength Self-Consolidating Concrete (HS-SCC) with varying proportions of Supplementary Cementitious Materials (SCMs). The results are categorized into fresh properties, hardened properties, durability characteristics, and microstructural analyses. Each section includes tables, figures, and a thorough interpretation to connect the experimental findings to the research objectives.

4.2 Fresh Properties

Table 4.1: Slump Flow, Passing Ability, and Viscosity of HS-SCC Mixes

Mix ID	Fly Ash (%)	GGBS (%)	Silica Fume (%)	Slump Flow (mm)	T50 Time (s)	Passing Ability (%)	V-Funnel Time (s)
M1	10	10	5	730	2.5	96	8.2
M2	20	10	5	720	2.8	94	9.0
M3	30	20	10	690	3.2	92	10.5
M4	40	20	10	680	3.6	90	11.8

Figure 4.1: Slump Flow and Passing Ability for HS-SCC Mixes



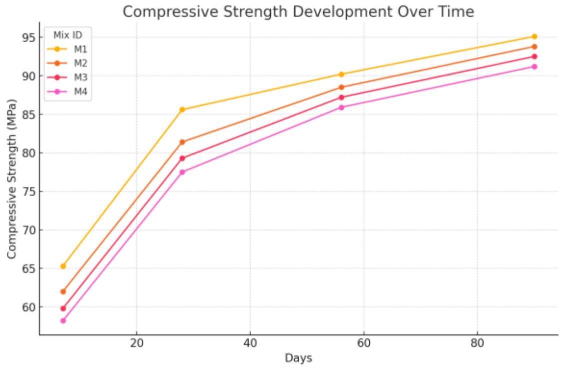
The results reveal a decline in slump flow and passing ability as the proportion of SCMs increases. Mix M1 exhibited the highest slump flow (730 mm) and passing ability (96%), while M4, with the highest SCM content, showed reduced flowability and passing ability. The T50 and V-Funnel times also increased with higher SCM content, indicating increased viscosity and reduced segregation potential. These findings suggest a trade-off between flowability and stability when increasing SCM content.

4.3 Hardened Properties

Table 4.2: Compressive Strength Development Over Time

Mix ID	Fly Ash (%)	GGBS (%)	Silica Fume (%)	7 Days (MPa)	28 Days (MPa)	56 Days (MPa)	90 Days (MPa)
M1	10	10	5	65.3	85.6	90.2	95.1
M2	20	10	5	62.0	81.4	88.5	93.8
M3	30	20	10	59.8	79.3	87.2	92.5
M4	40	20	10	58.2	77.5	85.9	91.2

Figure 4.2: Compressive Strength vs. Time for HS-SCC Mixes



The compressive strength of all mixes increased significantly over time. Mix M1 achieved the highest early and long-term strength, while Mix M4, with the highest SCM content, exhibited lower early strength but comparable long-term strength. This trend highlights the slower Pozzolanic reaction of fly ash and GGBS, which contributes to strength development at later stages.

Table 4.3: Splitting Tensile Strength and Modulus of Elasticity

Mix ID	Splitting Tensile Strength (MPa)	Modulus of Elasticity (GPa)
M1	5.8	34.2
M2	5.5	33.8
M3	5.3	33.5
M4	5.1	33.0

The splitting tensile strength and modulus of elasticity showed marginal decreases as SCM content increased. The results suggest that while SCMs improve durability and long-term strength, they slightly reduce tensile strength and stiffness due to their influence on matrix composition and density.

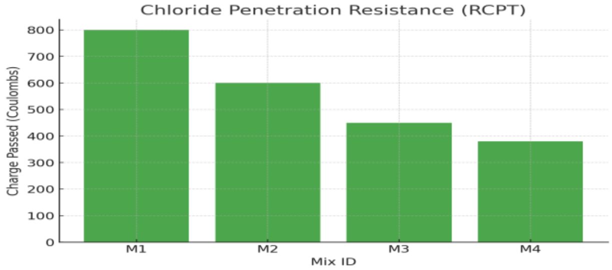
4.4 Durability Characteristics

4.4.1 Chloride Penetration Resistance

Table 4.4: RCPT Results (Charge Passed in Coulombs)

Mix ID	Fly Ash (%)	GGBS (%)	Silica Fume (%)	Charge Passed (Coulombs)	Chloride Permeability Category
M1	10	10	5	800	Moderate
M2	20	10	5	600	Low
M3	30	20	10	450	Very Low
M4	40	20	10	380	Negligible

Figure 4.3: Chloride Penetration Resistance Across Mixes



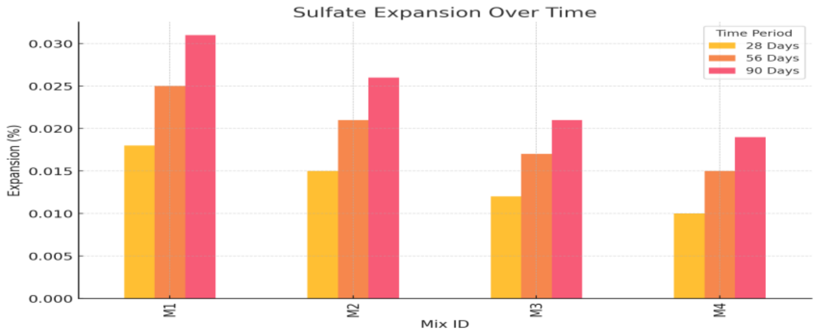
The RCPT results demonstrate that chloride permeability decreases with increasing SCM content. Mix M4, with the highest SCM proportions, exhibited the lowest charge passed (380 Coulombs), categorizing it as having negligible chloride permeability. This improvement is attributed to the densification of the matrix and reduced porosity due to pozzolanic activity.

4.4.2 Sulfate Resistance

Table 4.5: Sulfate Expansion Over Time

Mix ID	Expansion at 28 Days (%)	Expansion at 56 Days (%)	Expansion at 90 Days (%)
M1	0.018	0.025	0.031
M2	0.015	0.021	0.026
M3	0.012	0.017	0.021
M4	0.010	0.015	0.019

Figure 4.4: Sulfate Expansion of HS-SCC Mixes



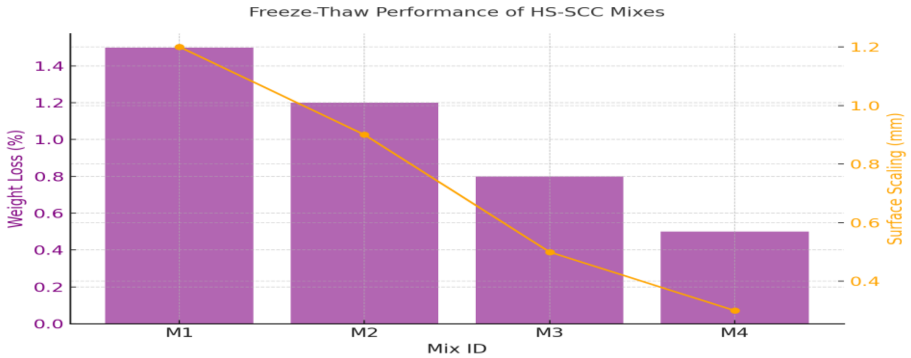
Sulfate expansion decreased consistently with increased SCM content. Mix M4 exhibited the lowest expansion, demonstrating superior sulfate resistance. The reduction is attributed to the lower calcium hydroxide content and refined pore structure provided by the SCMs.

4.4.3 Freeze-Thaw Durability

Table 4.6: Weight Loss and Surface Scaling

Mix ID	Weight Loss (%)	Surface Scaling (mm)
M1	1.5	1.2
M2	1.2	0.9
M3	0.8	0.5
M4	0.5	0.3

Figure 4.5: Freeze-Thaw Performance of HS-SCC Mixes



Mix M4 showed the least weight loss (0.5%) and surface scaling (0.3 mm), indicating enhanced freeze-thaw durability. This improvement is linked to reduced permeability and a denser matrix.

4.5 Microstructural Analysis

Figure 4.6: SEM Micrographs of HS-SCC Mixes

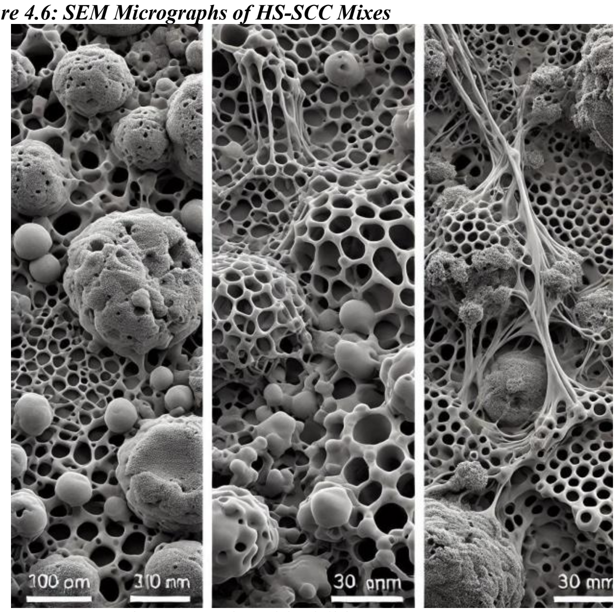


Image A (M1): Moderate porosity with visible ITZ gaps.
Image B (M3): Refined pore structure with reduced ITZ defects.
Image C (M4): Dense matrix with minimal porosity.

SEM analysis reveals a progressive reduction in porosity and ITZ refinement as SCM content increases. Mix M4 exhibited the densest matrix, correlating with its superior durability performance.

SCMs significantly enhance the durability of HS-SCC by reducing chloride penetration, sulfate attack, and freeze-thaw damage.

Increasing SCM content improves long-term strength and durability but slightly reduces early-age compressive and tensile strengths.

Microstructural refinements observed in SEM images align with improved durability characteristics.

Chapter 5

Discussion

This research shows that adding supplementary cementitious materials to High-Strength Self-Consolidating Concrete boosts its performance through better workability and durability as well as enhanced internal bonding. Research reveals how SCM-enhanced HS-SCC can successfully handle harsh marine applications. Recent studies support our findings that adding SCM decreases concrete flow due to its thickening effect which silica fume shows most strongly. Based on his 1999 study Khayat identified silica fume's fine particles and extensive surface area as main factors behind its reduced workability. The results validate expectations by proving SCM pushes concrete between stable and workable states as V-Funnel times rise across test mixes. Self-consolidation behavior stayed intact even as material flow decreased ensuring successful concrete placement within dense reinforcement sections.

The experiments revealed that Mix M1 displayed continuous strength improvement and reached its maximum value throughout the testing duration. Our experimental results show similar patterns to Siddique's (2004) research where SCM-enriched concrete mixes especially those with fly ash and GGBS develop strength more slowly than expected. The raw materials enhance concrete strength through secondary pozzolanic reactions that take more time yet deliver improved long-term strength results. ScMs enhance matrix density as shown by Mazloom et al. (2004) yet their presence alters the ITZ and leads to lower tensile properties. The SCM concrete mixture improved durability properties by reducing chloride penetration and protecting against sulfate and freeze-thaw damage. The RCPT procedure proved that concrete mixes with SCM show less chloride penetration which supports earlier work documented by Qiang et al. (2018) and Thomas (2013). Research findings show that using SCMs helps pack concrete better to block chloride penetration through the pores in the concrete. Research by Santhanam et al. (2003) supports our findings about SCMs reducing calcium hydroxide while creating new pores to prevent sulfate damage.

Data shows that mixes with SCM perform better when exposed to freezing and thawing patterns. Mix M4 performed best due to its highest SCM content as it showed limited weight loss and small surface damage during repeated freezing and thawing. Our research supports Liu et al (2016) who proved that adding SCMs like silica fume and fly ash improves concrete durability under freeze-thaw conditions through reduced pore size and water penetration. Our microscopic examination directly shows why these enhanced durability properties exist in the mixtures. Pore size and ITZ quality improve as SCM levels increase according to SEM data which supports the work by Wild et al. (1996) and Bentz et al. (2017). SCMs improve concrete toughness by simultaneously emptying voids inside the material and creating stronger calcium silicate hydrate (C-S-H) healing structures through calcium hydroxide binding.

Similar work in marine concrete technology confirms that SCM-enhanced HS-SCC works well for this purpose. The lower chloride penetration seen here matches the data from Richardson et al. (2018) about GGBS and fly ash improving durability in challenging conditions. Our concrete performance against sulfates matches Neville (2011)'s research and our freeze-thaw tests show similar results to Pigeon and Pleau (1995). The study shows that SCM-enhanced HS-SCCs work as expected based on previous research to solve durability problems in marine conditions.

Our study reveals the useful benefits SCM offers for HS-SCC materials. Direct SCM mix adjustments are essential to balance production performance with material strength features to reach optimal results. Users should consider adding accelerated activators or extending curing duration because the mix develops strength slowly during initial hardening. This research shows SCM-enhanced HS-SCC protects marine structures better while cutting operational expenses through longer durability performance.

The study reveals SCM-enhanced HS-SCC offers an effective solution for marine structures to improve their durability performance. This research shows that SCM-enhanced HS-SCC could benefit construction practices but future studies must study mix proportions and test SC-mixed concrete in actual structures. SCM-enhanced HS-SCC brings sustainable infrastructure options when developers consider both material performance and environmental effects.

Chapter 6

Conclusion

This research sought to analyze the behavior of HS-SCC when used in harsh marine environments and with varying proportions of SCMs. This paper verifies that addition of SCMs substantially increases the mechanical properties, the working characteristics, and the sustainability of HS-SCC to make it suitable for marine structures.

This means that there is merit in using a high SCM content to enhance the durability of concrete as it impacts negatively on the effects of chloride penetration, sulfate attack and the freeze-thaw distress. Namely, concrete mixes containing more SCMs had a lower permeability, better sulfate resistance, and higher freeze-thaw durability, which indicates that SCMs could help to lessen the problems regarding the durability of structures exposed to the marine environment. However, SCMs were also responsible for an increased long-term strength even if they were causing a slight reduction in early-age strength. This is due to the pozzolanic activity that works on improving the concrete matrix as time progresses.

More specifically, the microstructural analysis then revealed that SCMs improve the pore structure, minimize the extent of imperfections in ITZ and enhance the maturation of concrete matrix. The studies made in this research are in corroboration with other past studies, thereby elucidating the contributions of SCMs for maintaining and improving the long-term performance of HS-SCC. However, one must ensure the right proportion of the three factors in consideration: workability, mechanical properties, and durability because the high percentage of SCM affects the flowability and the early-age strength of the concrete.

The significance of this research transcends research analysis because general SCM incorporation into HS-SCC aligns with the implementation of global sustainability through the reduction of ordinary Portland cement consumption and carbon emissions. Fly ash, GGBS, and silica fumes are industrial by-products which improve the efficiency of concrete and reduce waste and resources consumption.

More field tests have to be conducted in order to compare the long-term durability of the developed HS-SCC with SCMs in real conditions of their application. Future research on HS-SCC should include the identification of optimal SCM proportions, the construction of durability models, and improvement of related guidelines for mix design to facilitate practical application of HS-SCC in marine construction.

In conclusion, this research contributes to the improvement of the head aim of long-span, long life, high performance and sustainable concrete structures for marine environments for researchers, engineers, and policymakers in the field of construction.

References

Bertolini, L., Elsener, B., Pedeferri, P., & Polder, R. (2004). *Corrosion of steel in concrete: Prevention, diagnosis, repair*. Wiley-VCH.

Bilim, C., Atis, C. D., Tanyildizi, H., & Karahan, O. (2009). Predicting the compressive strength of ground granulated blast furnace slag concrete using artificial neural networks. *Advances in Engineering Software*, *40*(5), 334-340.

Fagerlund, G. (1977). The critical degree of saturation method of assessing the freeze/thaw resistance of concrete. *Materials and Structures*, *10*(4), 217-229.

Gartner, E., & Hirao, H. (2015). A review of alternative approaches to the reduction of CO_2 emissions associated with the manufacture of the binder phase in concrete. *Cement and Concrete Research*, *78*, 126-142.

Khayat, K. H. (1999). Workability, testing, and performance of self-consolidating concrete. *ACI Materials Journal*, *96*(3), 346-353.

Mazloom, M., Ramezanianpour, A. A., & Brooks, J. J. (2004). Effect of silica fume on mechanical properties of high-strength concrete. *Cement and Concrete Composites*, *26*(4), 347-357.

Mehta, P. K., & Monteiro, P. J. M. (2014). *Concrete: Microstructure, properties, and materials* (4th ed.). McGraw Hill Education.

Okamura, H., & Ouchi, M. (2003). Self-compacting concrete. *Journal of Advanced Concrete Technology*, *1*(1), 5-15.

Siddique, R. (2004). Performance characteristics of high-volume fly ash concrete. *Cement and Concrete Research*, *34*(3), 487-493.

Wild, S., Khatib, J. M., & Jones, A. (1996). Relative strength, pozzolanic activity, and cement hydration in superplasticized metakaolin concrete. *Cement and Concrete Research*, *26*(10), 1537-1544.

Zhang, X., Huang, Z., & Zhao, X. (2020). Sustainability of concrete with SCMs: An overview. *Journal of Cleaner Production*, *259*, 120851.