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Performance Evaluation of High-Strength Self-Compacting Concrete Incorporating Industrial and Agricultural By-products under Elevated Temperatures

[1]Mukesh, [2]Rakesh Kumar
[1]M.Tech. Scholar, [2]Assistant Professor
Department of CE
BRCM College of Engineering and Technology, Bahal (Bhiwani) India

Abstract

The construction sector is increasingly focused on materials that not only deliver superior mechanical performance but also address the pressing demand for sustainability. Conventional vibrated concrete often struggles with inadequate compaction in heavily reinforced or complex sections, leading to reduced durability and long-term performance issues. To overcome these shortcomings, this study investigates the development of High-Strength Self-Compacting Concrete (HSSCC) by incorporating a combination of industrial and agricultural by-products. Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), Marble Sludge Powder (MSP), Silica Fume (SF), Quartz Sand (QS), and Coir Pith Ash (CPA) were introduced either as supplementary cementitious materials or as fine aggregate replacements. Natural fibers such as coir and kenaf, as well as polypropylene fibers, were also employed individually and in hybrid forms to further enhance the tensile and flexural response.

A comprehensive experimental program was carried out to evaluate both fresh and hardened properties of the proposed mixes. Workability was assessed through slump flow, V-funnel, L-box, and compaction factor tests, while mechanical performance was studied by compressive, split tensile, and flexural strength evaluations. Durability aspects were examined using acid, sulphate, and chloride resistance tests, as well as water absorption and permeability studies. In addition, the behavior of the mixes at elevated temperatures up to 300 °C was investigated to simulate fire exposure conditions. Microstructural analysis using SEM and XRD provided further insight into the internal stability of the optimized concretes. To complement the laboratory investigations, an Artificial Neural Network (ANN) model was developed to predict compressive strength based on six key mix parameters, offering a data-driven perspective for strength estimation.

The results revealed that the inclusion of GGBS and FA improved both strength and durability, while polypropylene fibers significantly enhanced tensile resistance without compromising workability. Hybrid fiber combinations produced synergistic effects, with mixes such as M24 and M29 showing the most promising balance between compressive strength and ductility. Concrete specimens incorporating mineral admixtures retained considerable strength after exposure to 300 °C, confirming their thermal stability compared to conventional high-strength vibrated concrete. The ANN model predictions showed close agreement with experimental data, indicating its suitability as a practical design tool.

Overall, this research demonstrates that HSSCC formulated with sustainable admixtures and optimized fiber reinforcement not only meets the performance requirements for advanced structural applications but also contributes to eco-friendly construction practices.

Keywords: *High-Strength Self-Compacting Concrete, Fly Ash, Ground Granulated Blast Furnace Slag, Silica Fume, Marble Sludge Powder, Quartz Sand, Fibers, Durability, Elevated Temperature, ANN Prediction*

Introduction

Background on the Limitations of Conventional Vibrated Concrete

For several decades, conventional vibrated concrete has served as the backbone of construction projects worldwide. While it provides adequate strength for most structural applications, it often encounters serious limitations in practice. In areas with dense reinforcement or intricate formwork, proper compaction becomes difficult to achieve. Mechanical vibration, though intended to eliminate air voids and improve homogeneity, frequently leads to segregation, honeycombing, or inconsistent strength development. These defects reduce both the durability and the long-term performance of concrete structures, especially in critical components such as high-rise columns, long-span bridges, and precast elements.

Evolution of Self-Compacting Concrete (SCC) and Its Advantages

To address these shortcomings, researchers in Japan introduced Self-Compacting Concrete (SCC) in the late 1980s. Unlike vibrated concrete, SCC flows under its own weight, filling even the most congested reinforcement zones without the need for vibration. This innovation not only improves uniformity and surface finish but also minimizes labor requirements and human error during placement. With superior workability and resistance to segregation, SCC has become an attractive option for modern construction projects that demand both efficiency and high quality. International guidelines, including those from EFNARC and ACI, have further standardized its use, accelerating its adoption across structural and infrastructure applications.

Need for High-Strength SCC (HSSCC) in Modern Infrastructure

The global trend towards taller, larger, and more complex structures has created a demand for concrete that combines excellent flowability with very high strength. High-Strength Self-Compacting Concrete (HSSCC) meets this requirement by integrating the benefits of SCC with compressive strengths exceeding those of conventional mixes. Such materials are crucial for reducing cross-sectional dimensions, supporting heavy loads, and extending service life in demanding environments. However, designing HSSCC requires careful optimization of its constituents, as higher fines content and lower water-to-binder ratios must be balanced to ensure both flowability and strength.

Environmental Motivation: Use of Industrial and Agricultural Wastes

Another driving factor behind the development of HSSCC is the pressing need for sustainable construction practices. Cement production contributes significantly to global CO_2 emissions, while industrial and agricultural by-products often pose disposal challenges. Incorporating materials such as Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), Marble Sludge Powder (MSP), Coir Pith Ash (CPA), and natural or synthetic fibers offers a dual benefit: enhancing the performance of concrete while reducing environmental impact. These supplementary materials not only improve workability and strength but also contribute to waste management, conservation of natural resources, and reduction of embodied energy in construction.

Research Gap

Despite the proven advantages of SCC and the increasing use of supplementary materials, limited research exists on the behavior of HSSCC under elevated temperatures, particularly when multiple industrial and agricultural admixtures are combined. Fire exposure is a critical safety concern for modern infrastructure, and understanding the thermal performance of HSSCC is essential to ensure structural reliability in such conditions. This gap highlights the need for systematic experimental studies that evaluate both the mechanical and durability characteristics of HSSCC when subjected to high temperatures, supported by microstructural analysis and predictive modeling.

Literature Review

The development of High-Strength Self-Compacting Concrete (HSSCC) has been extensively studied in the context of performance optimization and sustainability. Traditional High-Performance Concrete (HPC) achieves superior compressive strength and durability by lowering the water-to-binder ratio and incorporating admixtures; however, its brittleness and low tensile resistance remain limitations. Studies have shown that the inclusion of fibers—natural, synthetic, or hybrid—improves flexural strength, ductility, and crack resistance, thereby extending HPC's structural applications [Storm et al., 2021; Yan et al., 2021].

Research on fiber orientation and distribution in advanced concretes highlights their influence on mechanical performance. For instance, extrusion and 3D printing studies confirm that nozzle geometry and fiber dosage affect alignment, which in turn governs tensile and flexural strength [Arunothayan et al., 2021]. Polypropylene and basalt fibers, in particular, have demonstrated improved resistance to spalling at elevated temperatures, as they promote micro-crack formation and enhance permeability during heating [Zhang et al., 2021; Alaskar et al., 2021]. Similarly, natural fibers such as coir and flax have been shown to increase ductility and crack-bridging capacity, though their tendency to absorb water can reduce compressive strength [Kouta et al., 2021].

Industrial by-products such as Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), and Silica Fume (SF) have been widely adopted in SCC formulations due to their pozzolanic activity and ability to refine pore structure. Studies confirm that FA contributes to long-term strength development and sulfate resistance, while GGBS improves durability and reduces chloride permeability [Kathirvel et al., 2021]. Marble sludge powder (MSP) and other stone waste materials have also been evaluated as fine aggregate replacements, with encouraging results in terms of both mechanical properties and sustainability outcomes.

While numerous investigations have addressed the fresh and hardened properties of SCC and HPC with mineral admixtures, comparatively fewer have focused on the combined effect of multiple supplementary materials under high-temperature conditions. Existing studies report that the thermal degradation of high-strength concrete is significantly influenced by the type and dosage of mineral admixtures, with GGBS- and FA-based concretes showing better residual strength retention compared to conventional mixes [Zhang et al., 2021]. However, comprehensive experimental evidence for HSSCC incorporating multiple industrial and agricultural by-products, particularly under thermal exposure, remains limited.

Recent work has also emphasized the role of computational models, particularly Artificial Neural Networks (ANN), in predicting concrete properties. Several authors have demonstrated that ANN models can reliably forecast compressive strength using mix design parameters, curing conditions, and test results as input variables [Dingqiang et al., 2021]. This predictive capability allows for efficient mix optimization and reduces dependence on exhaustive laboratory testing.

Taken together, the literature indicates that while individual admixtures and fibers are well studied, there is a clear gap in understanding the synergistic performance of HSSCC mixes that combine industrial by-products, agricultural wastes, and fiber reinforcement, particularly under elevated temperature exposure. Addressing this gap forms the central motivation of the present study.

Materials and Methodology

Materials

The experimental program employed a carefully selected combination of conventional and supplementary materials to develop High-Strength Self-Compacting Concrete (HSSCC) mixes.

- **Cement**: Ordinary Portland Cement (OPC) of 43 grade conforming to IS: 8112 was used as the primary binder. This grade was chosen due to its stable composition and ability to achieve consistent strength gain.
- **Fly Ash (FA)**: Class F fly ash obtained from a thermal power plant was incorporated as a supplementary cementitious material. Its pozzolanic activity and fine particle size contribute to improved long-term strength and durability.
- **Ground Granulated Blast Furnace Slag (GGBS)**: A by-product from steel manufacturing, GGBS was used to enhance durability and reduce chloride permeability. Its latent hydraulic properties make it a valuable cement replacement.
- **Micro Silica (Silica Fume, SF)**: Ultra-fine amorphous silica powder was added at controlled dosages to refine pore structure, improve packing density, and increase compressive strength.
- **Marble Sludge Powder (MSP)**: Industrial marble waste was ground into fine powder and used as a partial replacement for fine aggregates. MSP helps in reducing environmental waste while improving particle packing.
- **Coir Pith Ash (CPA)**: Derived from burning coconut coir pith, CPA was included as an agricultural by-product. It provides additional silica and alumina while supporting waste utilization.
- **Fibers**: To address the brittleness of high-strength mixes, different types of fibers were incorporated:
    - *Natural fibers*: Coir and kenaf fibers were used to enhance ductility and crack-bridging capacity.
    - *Synthetic fibers*: Polypropylene fibers were added for their high tensile strength, low water absorption, and spalling resistance at elevated temperatures.

Aggregates consisted of clean, locally available river sand (Zone II) as fine aggregate and crushed stone (20 mm downsize) as coarse aggregate. A polycarboxylate-based superplasticizer was used to achieve the desired workability without increasing water content.

Mix Design Procedure

The mix proportions were determined using a modified version of the **Nan Su method**. This approach emphasizes aggregate packing density and the balance between fine and coarse fractions to achieve both high flowability and mechanical performance. Unlike conventional SCC design procedures that treat mineral admixtures as a single component, this study considered FA and GGBS separately to better capture their individual contributions.

For all mixes, Micro Silica was fixed at 8% by weight of cement, based on preliminary trials and EFNARC recommendations. MSP and CPA were introduced in varying proportions as partial replacements for fine aggregates, while fiber dosages were optimized based on trial batches to minimize workability loss. The water-to-binder (w/b) ratio was adjusted to achieve the target compressive strength.

The target grade for all mixes was **M70**, representing a high-strength category suitable for demanding structural applications. Control mixes of conventional high-strength vibrated concrete (HSVC) were also prepared for comparison.

Experimental Methods

Fresh Properties

The workability and flowability of HSSCC mixes were assessed using the following EFNARC-recommended tests:

- **Slump flow**: to measure filling ability and detect segregation.
- **V-funnel**: to evaluate viscosity and flow time.
- **L-box and U-box tests**: to assess passing ability in reinforcement congestion.
- **Compaction factor test**: to provide an overall index of workability.

Mechanical Properties

- **Compressive strength** was tested on cube specimens at 7, 28, and 90 days in accordance with IS: 516.
- **Split tensile strength** was measured using cylindrical specimens to determine tensile resistance.
- **Flexural strength** tests were carried out on beam specimens to evaluate bending resistance and crack formation behavior.

Durability Studies

Concrete durability was assessed by immersing specimens in aggressive solutions and measuring weight loss and residual strength:

- **Acid resistance**: using HCl and H_2SO_4 solutions.
- **Sulphate resistance**: using $MgSO_4$ solution.
- **Chloride resistance**: by immersion in NaCl solution.
- **Alkali resistance**: using NaOH and related alkaline environments.
  Water absorption, porosity, and permeability were also measured to provide further insights into durability performance.

High-Temperature Studies

To evaluate fire resistance, specimens were exposed to temperatures up to **300 °C** in a controlled muffle furnace. Residual compressive strength, mass loss, surface condition, and spalling tendency were recorded after cooling.

Microstructural Analysis

Selected mixes were examined using **Scanning Electron Microscopy (SEM)** to observe pore structure, crack patterns, and bonding of fibers. **X-ray Diffraction (XRD)** was used to analyze the crystalline phases formed during hydration and after thermal exposure.

Artificial Neural Network (ANN) Modeling

In addition to laboratory testing, an **ANN-based predictive model** was developed to estimate compressive strength. Twenty experimental datasets were used to train the model, with six key mix parameters (cement content, FA, GGBS, SF, water content, and fiber dosage) serving as input variables. The compressive strength was taken as the output parameter.

The ANN employed a feed-forward back-propagation algorithm with optimized hidden layers to minimize prediction error. The performance of the model was evaluated using mean squared error (MSE) and correlation coefficient (R^2) values. This computational approach provided insight into the complex interactions between multiple admixtures and their impact on strength development.

Table 1. Mix Proportions for Control and Supplementary Admixture HSSCC Mixes (kg/m³)

Mix ID	Cement	FA	GGBS	Micro Silica	MSP	CPA	Fine Aggregate	Coarse Aggregate	Water	Superplasticizer	w/b Ratio
M0 (Control HSVC)	500	–	–	–	–	–	750	1050	150	6.0	0.30
M12	420	80	–	40	20	–	720	1020	150	6.5	0.28
M14	400	100	–	40	30	–	710	1020	150	6.5	0.28
M24	380	–	120	40	20	–	700	1010	150	6.8	0.27
M29	360	–	140	40	30	10	690	1000	150	7.0	0.27

Note: FA = Fly Ash; GGBS = Ground Granulated Blast Furnace Slag; MSP = Marble Sludge Powder; CPA = Coir Pith Ash.

Table 2. Fiber Reinforcement Details for HSSCC Mixes

Mix ID	**Coir Fiber (% by vol.)**	**Kenaf Fiber (% by vol.)**	**Polypropylene Fiber (% by vol.)**	**Hybrid Fiber System**
M12	0.25	–	–	–
M14	–	0.25	–	–
M24	–	–	0.20	–
M29	0.15	–	0.15	Coir + PP

Table 3. Compressive Strength of HSSCC Mixes (MPa)

Mix ID	**7 Days**	**28 Days**	**90 Days**
M0 (Control HSVC)	54.2	71.0	74.5
M12	58.5	76.8	82.1
M14	57.3	75.6	80.4
M24	61.0	79.5	85.2
M29	62.4	81.2	87.0

Table 4. Split Tensile Strength of HSSCC Mixes (MPa)

Mix ID	**7 Days**	**28 Days**	**90 Days**
M0 (Control HSVC)	3.8	5.2	5.6
M12	4.2	5.8	6.3
M14	4.0	5.6	6.1
M24	4.4	6.2	6.7
M29	4.6	6.5	6.9

Table 5. Flexural Strength of HSSCC Mixes (MPa)

Mix ID	**7 Days**	**28 Days**	**90 Days**
M0 (Control HSVC)	6.2	8.5	9.0
M12	6.8	9.3	10.2
M14	6.6	9.0	9.8
M24	7.2	9.8	10.7
M29	7.5	10.2	11.0

Results

1. Fresh Properties

The self-compacting nature of the developed mixes was evaluated using slump flow, V-funnel, L-box, and compaction factor tests. All HSSCC mixes demonstrated satisfactory flowability within EFNARC guidelines.

- **Slump flow** values for optimized mixes (M12, M14, M24, M29) ranged between 660–710 mm, indicating excellent filling ability and minimal segregation. In comparison, the control HSVC required mechanical vibration to achieve compaction and did not attain equivalent spread.
- **V-funnel times** varied between 8–11 seconds, suggesting adequate viscosity for stable flow. Mixes incorporating Micro Silica and GGBS (e.g., M24, M29) exhibited slightly longer flow times due to increased paste cohesiveness.
- **L-box ratios** exceeded 0.9 for all HSSCC mixes, reflecting superior passing ability through simulated reinforcement. This contrasts with the control mix, which showed reduced flow without vibration.
- **Compaction factor** tests further confirmed the self-consolidating ability of HSSCC, with values close to 1.0, while the control HSVC displayed lower indices due to its dependence on mechanical compaction.

These results confirm that the incorporation of FA, GGBS, and mineral admixtures, combined with optimized superplasticizer dosages, successfully produced highly workable HSSCC mixes.

2. Mechanical Properties

Compressive Strength

At all curing ages (7, 28, and 90 days), the HSSCC mixes outperformed the control HSVC. FA- and GGBS-based mixes exhibited steady strength gain, particularly beyond 28 days, due to their pozzolanic reactivity. The highest compressive strength was observed in mix M29 (87.0 MPa at 90 days), followed closely by M24 (85.2 MPa). Control HSVC, in contrast, reached only 74.5 MPa at 90 days.

Split Tensile Strength

Fiber incorporation played a critical role in enhancing tensile resistance. Coir and kenaf fibers provided additional ductility, while polypropylene fibers effectively controlled crack propagation. Mix M29, with a hybrid fiber system, recorded the highest split tensile strength (6.9 MPa at 90 days), showing a 20–25% improvement over the control.

Flexural Strength

Similar trends were observed in flexural performance. Fiber-reinforced mixes showed notable improvements, with M29 achieving 11.0 MPa at 90 days compared to 9.0 MPa for the control HSVC. The synergy of mineral admixtures and fibers not only increased load-carrying capacity but also enhanced post-cracking behavior, reducing brittleness typically associated with high-strength concretes.

3. Durability Performance

Durability assessments confirmed that HSSCC mixes incorporating FA, GGBS, and MSP were more resistant to aggressive environments than the control HSVC.

- **Acid resistance**: Weight loss in HSSCC specimens immersed in HCl and H_2SO_4 was significantly lower than in the control mix. GGBS-rich mixes exhibited the best resistance due to reduced calcium hydroxide content and denser microstructure.
- **Sulphate resistance**: HSSCC mixes showed minimal expansion or surface deterioration when exposed to $MgSO_4$ solutions, with strength retention above 90% at 90 days. The control mix suffered more pronounced degradation.
- **Chloride resistance**: Chloride penetration was reduced by nearly 30% in mixes containing GGBS and FA compared to HSVC. This improvement is attributed to refined pore structures and lower permeability.
- **Water absorption and permeability**: Both properties were substantially reduced in

HSSCC mixes, especially M24 and M29, confirming the densification effect of micro silica and mineral admixtures.

Overall, the results establish HSSCC as more durable and suitable for aggressive service environments compared to conventional high-strength concretes.

4. Elevated Temperature Behavior

The residual strength of HSSCC was evaluated after exposure to 100 °C, 200 °C, and 300 °C.

- **Residual Compressive Strength**: Up to 200 °C, strength reduction was moderate (less than 10% loss). At 300 °C, reductions were more significant but still within acceptable limits for structural integrity. Mix M29 retained approximately 75% of its original compressive strength, whereas the control HSVC retained only 60%.
- **Weight Loss**: HSSCC mixes exhibited lower weight loss compared to HSVC, attributed to improved microstructural stability provided by mineral admixtures.
- **Spalling Resistance**: Polypropylene fibers proved particularly effective, as they melted at elevated temperatures, creating micro-channels that relieved vapor pressure and reduced explosive spalling.

These findings suggest that HSSCC formulations with FA, GGBS, and fibers can maintain functional performance under moderate fire exposure conditions.

5. ANN Prediction

The ANN model, trained with six mix parameters (cement, FA, GGBS, silica fume, water, and fiber dosage), showed strong predictive accuracy for compressive strength.

- The model achieved an **R^2 value above 0.95**, indicating a close correlation between experimental and predicted strengths.
- The **mean squared error (MSE)** was low, confirming reliable convergence.
- Predicted values closely followed experimental trends, particularly for mixes M24 and M29, where deviations were within ±3%.

The ANN model thus demonstrates potential as a practical tool for forecasting compressive strength in complex HSSCC systems, reducing dependency on exhaustive laboratory trials while enabling rapid optimization.

Discussion

1. Effect of Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBS) on Strength and Durability

The inclusion of FA and GGBS had a significant influence on both the strength development and the durability characteristics of HSSCC. Fly Ash, owing to its slow pozzolanic reactivity, contributed less to early-age strength but was instrumental in enhancing later-age properties. Mixes containing FA showed a marked strength gain between 28 and 90 days, consistent with secondary hydration reactions where calcium hydroxide is consumed to form additional calcium silicate hydrate (C–S–H). This densified the microstructure, reducing pore connectivity and improving long-term mechanical stability.

GGBS, on the other hand, demonstrated a more immediate effect. Its latent hydraulic properties, when activated in the alkaline environment of cement hydration, provided both early and later strength contributions. In terms of durability, GGBS-rich mixes exhibited superior resistance to acid and chloride attack compared to FA-based mixes. This can be attributed to the reduced calcium hydroxide content and lower permeability, which limit the ingress of aggressive ions. Together, FA and GGBS not only enhanced mechanical properties but also imparted resilience to chemical degradation, making them critical components in sustainable HSSCC formulations.

2. Role of Fibers: Individual vs. Hybrid Systems

The brittleness of high-strength concretes often limits their application in structures where tensile and flexural stresses are significant. The incorporation of fibers effectively addressed this limitation.

- **Individual fibers**: Coir and kenaf fibers enhanced ductility and delayed crack propagation but also introduced slight reductions in workability due to their hydrophilic nature. Polypropylene fibers, being hydrophobic and lightweight, improved crack control under tensile loads and showed notable benefits in spalling resistance at elevated temperatures.
- **Hybrid fibers**: The combined use of natural and synthetic fibers produced a synergistic effect. For instance, the hybrid mix M29 (coir + polypropylene) demonstrated higher tensile and flexural strengths than mixes with individual fibers. This improvement arises from the complementary action: natural fibers bridge larger cracks, while polypropylene controls micro-cracking, resulting in a multi-scale crack arresting system.

The outcome confirms that hybridization provides a balanced improvement in both strength and toughness, making it more effective than single-fiber reinforcement for HSSCC.

3. Performance of HSSCC vs. HSVC at Elevated Temperatures

When exposed to elevated temperatures, all concrete mixes experienced some strength loss due to dehydration of hydrates and microcracking. However, the extent of degradation differed markedly between HSSCC and the control HSVC.

The control HSVC showed a sharper decline in residual compressive strength, retaining only about 60% of its strength after exposure to 300 °C. In contrast, optimized HSSCC mixes retained up to 75% of their original strength. The improved thermal stability of HSSCC can be explained by the densified microstructure formed by supplementary materials, which reduces the rate of moisture migration and pore pressure buildup. Additionally, polypropylene fibers provided a self-relieving mechanism at high temperatures by melting and creating micro-channels, thereby reducing the risk of explosive spalling.

This superior thermal performance suggests that HSSCC is better suited for structures with potential fire exposure, enhancing both safety and service life.

4. Microstructural Observations (SEM and XRD Correlation)

Microstructural investigations provided valuable insights into the observed macroscopic behavior.

- **SEM analysis** revealed that mixes containing FA, GGBS, and silica fume had a denser matrix with fewer capillary pores compared to HSVC. The interfacial transition zone (ITZ) appeared more compact in HSSCC, with well-bonded fiber-matrix interfaces in fiber-reinforced mixes. This explains the improved strength and reduced permeability.
- **XRD patterns** confirmed the formation of additional C–S–H phases in FA- and GGBS-based mixes, while the intensity of calcium hydroxide peaks was reduced compared to HSVC. This indicates more efficient pozzolanic reactions and consumption of portlandite, aligning with the improved durability results.

The combined SEM–XRD evidence supports the conclusion that mineral admixtures refine the microstructure, strengthen the ITZ, and improve resistance to chemical and thermal degradation.

5. Sustainability Perspective: Reduction of Cement Consumption and Waste Utilization

Beyond technical performance, the environmental dimension of this study is significant. The partial replacement of cement with FA, GGBS, MSP, and CPA directly reduced cement consumption, thereby lowering CO_2 emissions associated with clinker production. Each of these supplementary materials also represents either an industrial by-product or an agricultural waste, and their utilization addresses the pressing challenge of waste management.

Marble sludge powder, often considered an environmental hazard due to disposal issues, was effectively recycled into the concrete matrix without compromising strength. Similarly, coir pith ash, derived from agricultural residues, was valorized as a cement substitute, offering a pathway for rural waste utilization. Fiber reinforcement using natural sources like coir and kenaf further reduced reliance on synthetic materials, supporting a circular economy approach.

Thus, the development of HSSCC with multi-source waste materials not only enhances mechanical and durability performance but also aligns with global goals of sustainable construction and carbon footprint reduction.

Conclusion

The present investigation set out to develop and evaluate High-Strength Self-Compacting Concrete (HSSCC) mixes that not only achieve superior structural performance but also incorporate industrial and agricultural by-products for sustainability. The outcomes clearly demonstrate that optimized mix designs, particularly **M24 and M29**, outperformed conventional high-strength vibrated concrete (HSVC) across all key performance indicators. These mixes exhibited higher compressive, split tensile, and flexural strengths, coupled with enhanced durability against acid, sulphate, and chloride attack. The integration of mineral admixtures such as Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), Micro Silica, and Marble Sludge Powder (MSP), along with natural and synthetic fibers, proved crucial in refining microstructure and improving overall toughness.

One of the notable findings was the performance of HSSCC under thermal exposure. While all concretes experienced strength reduction when subjected to elevated temperatures, mixes incorporating FA and GGBS retained significant structural integrity even at **300 °C**, outperforming the control HSVC. This resilience was further aided by the inclusion of polypropylene fibers, which provided vapor relief channels and minimized the risk of explosive spalling. Such thermal stability underscores the suitability of HSSCC for critical infrastructure where fire resistance is a major design consideration.

The study also established the potential of computational modeling in mix design optimization. The **Artificial Neural Network (ANN)** model developed for compressive strength prediction exhibited high accuracy, with results closely matching experimental values. This validates ANN as a reliable supplementary tool for forecasting strength trends, reducing the dependence on extensive laboratory trials, and enabling faster decision-making in material selection.

From a practical standpoint, the research highlights the dual benefits of HSSCC: **performance enhancement and sustainability**. The partial replacement of cement with FA, GGBS, MSP, and Coir Pith Ash (CPA) not only reduced cement demand and associated CO_2 emissions but also provided a productive avenue for waste utilization. The successful application of natural fibers such as coir and kenaf further reinforces the role of renewable materials in advanced concrete technology.

In summary, the study confirms that HSSCC, particularly in optimized forms like M24 and M29, represents a sustainable, durable, and high-performing material suitable for modern infrastructure. Its ability to deliver mechanical excellence, withstand aggressive environments, and retain structural integrity under elevated temperatures makes it a viable alternative to traditional high-strength concrete in demanding construction scenarios.

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