Nano World Journal

https://doi.org/10.17756/nwj.2023-s3-092

Research Article

Open Access

Effect of Fiber on the Performance of Self-compacting Concrete with Fly Ash, GGBS, and Alccofine as Cementitious Materials

Raghavendra Dollaiah[1*], Ramesh Venu[1] and Pradeep Rajanna Hampannaver[2]

[1]Department of Civil Engineering, East Point College of Engineering and Technology, Bengaluru, Karnataka, India
[2]RICS School of Built Environment, Amity University, Mumbai, Maharashtra, India

[*]Correspondence to:
Raghavendra Dollaiah
Department of Civil Engineering,
East Point College of Engineering and Technology,
Bengaluru, Karnataka, India.
E-mail: raghavendra.d67@gmail.com

Received: July 28, 2023
Accepted: October 17, 2023
Published: October 19, 2023

Citation: Dollaiah R, Venu R, Hampannaver PR. 2023. Effect of Fiber on the Performance of Self-compacting Concrete with Fly Ash, GGBS, and Alccofine as Cementitious Materials. *NanoWorld J* 9(S3): S500-S509.

Copyright: © 2023 Dollaiah et al. This is an Open Access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CCBY) (http://creativecommons.org/licenses/by/4.0/) which permits commercial use, including reproduction, adaptation, and distribution of the article provided the original author and source are credited.

Published by United Scientific Group

Abstract

This research study focuses on investigating the effects of incorporating hybrid fibers and supplementary cementitious materials (SCMs) on the performance of self-compacting concrete (SCC). The study evaluates four different SCC mixes with varying compositions, including 100% cement, cement with steel fiber and polypropylene fiber (PPF), and mixes with a combination of cement and ground granulated blast-furnace slag (GGBS). The research aims to comprehend the influence of these additives on fresh concrete properties, mechanical properties (compressive strength, split tensile strength, and flexural strength), and behaviour under elevated temperatures of 200 °C and 300 °C. Additionally, microstructural analyses were conducted to understand the complex material interactions within the concrete matrix. The methodology involves casting, curing, and testing of the SCC mixes, adhering to relevant standards and guidelines. The fresh concrete properties revealed variations in workability, while mechanical tests showcased improvements in strength and durability due to fiber and GGBS additions. Elevated temperature tests demonstrated the mixes' performance under thermal stress, with fiber-reinforced mixes exhibiting enhanced resistance. Microstructural analyses elucidated the presence of different phases, including C-S-H gel, ettringite, hydrated and unhydrated cement paste, voids, and microcracks. Key findings underline the benefits of hybrid fibers and GGBS in enhancing mechanical properties and elevated temperature resistance. The microstructural analyses provided insights into the complex interactions among constituents. The study concludes that a careful selection of fiber types and SCMs can significantly improve SCC's overall performance, making it suitable for various construction applications. The findings contribute to a deeper understanding of SCC's behavior, particularly under challenging conditions, offering valuable insights for optimizing mix designs and achieving desired performance characteristics.

Keywords

Self-compacting concrete, Steel fiber, Polypropylene fiber

Introduction

SCC stands as a pivotal advancement in contemporary construction practices. In a departure from conventional concrete, SCC addresses the multifaceted challenges inherent to concrete placement and compaction through its remarkable ability to flow and consolidate under its own weight, effectively filling intricate formworks without the need for mechanical consolidation [1]. This revolutionary material transcends the limitations of traditional concrete placement techniques, offering an unprecedented level of workability, uniformity, and aesthetic quality, reshaping the landscape of modern construction practices [2]. The significance of SCC resonates profoundly across modern construction domains by redefining established methodologies. It streamlines the construction process

by completely eliminating the labor-intensive compaction phase, effectively eradicating the risk of defects while ensuring consistent quality and structural integrity [3, 4]. SCC's exceptional flowability not only reduces noise pollution and vibration during placement but also diminishes wear and tear on formworks, contributing to safer, more efficient, and environmentally conscious construction practices [5]. Despite its manifold advantages, the optimization of SCC's mechanical properties remains a compelling challenge that researchers and engineers grapple with. Striking the delicate balance between desirable strength, enduring durability, and resistance to diverse environmental and load-induced stresses stands as an imperative objective in advancing SCC's performance envelope. The integration of SCMs, such as fly ash, GGBS, and alccofine, represents an enticing avenue to elevate SCC's performance attributes to new heights [6, 7]. However, a critical research void persists, demanding a more profound understanding of the potential synergistic interactions that arise from combining hybrid fibers with these cementitious materials, and their consequential impact on the holistic behavior of SCC [8]. Embarking on this explorative research journey, the primary objective is to unravel and enhance the performance of SCC through the informed integration of cementitious materials (fly ash, GGBS, alccofine) and hybrid fibers (steel fibers and PPF). The research endeavors to systematically accomplish a series of interconnected milestones like, conscientiously evaluate the intricate influence exerted by SCMs on the initial and long-term mechanical properties of SCC. Delve into the intricate nuances surrounding hybrid fiber incorporation, meticulously deciphering its impact on SCC's workability, strength, and enduring resilience. Subject SCC mixtures to the crucible of elevated temperature scenarios, particularly those occurring at 200 °C and 300 °C, revealing their response to extreme thermal stresses. Conduct a comprehensive dissection of SCC's internal microstructure, teasing out the subtle interactions among its myriad constituents to enrich the tapestry of understanding. Spanning a comprehensive spectrum, the research's canvas encompasses an intricate array of meticulously designed experiments. These experiments traverse the entire lifecycle of SCC, encompassing the process of casting, meticulous curing regimes, and a battery of precision tests to scrutinize each mix's unique characteristics. The scope extends across a panorama of assessments, incorporating the meticulous evaluation of fresh concrete properties, nuanced mechanical attributes, steadfast behavior under the duress of elevated temperatures, and a meticulous dissection of the intricate microstructural characteristics that weave SCC's intricate fabric. The research outcomes will weave a tapestry of knowledge, extending a guiding hand to optimize mix designs and ushering SCC into new vistas of efficacy across the myriad canvas of construction scenarios.

Recently, nanotechnology has brought unique performance to materials, and nanoparticles (NPs) have been extensively used in SCC to increase performance and enhance its characteristics. A major reason for adding NPs to concrete composites, including SCC, is to enhance the microstructural characteristics. There is growing interest in nanoparticles, and some researchers are using them in SCC to modify the fresh, mechanical, and durability properties. In the construction sector, concrete's durability and sustainability are becoming increasingly important, and SCC has attracted a lot of attention for these reasons.

Powdered or colloidal nano-silica was the most popular form of NP. By adding NPs to SCC composites, the construction industry may be able to develop high-performance composites for efficient implementation. A typical dosage of NPs ranges from 0% to 5% of the cement or binder. The performance of SCC composites is generally impacted by different NP types. In addition to improved hydration of cement, (i) increased mechanical properties, (iii) better energy absorption and ductility, (iii) reduced water and gas permeability, (iv) a reduction in water and gas permeability, (v) improved corrosion resistance due to increased electrical resistance, (vi) improved resistance to extreme environmental conditions are the major modifications and enhancements resulting from the addition of NPs types.

Literature review

Exploration of SCC: properties, advantages, and applications

The last decade has witnessed substantial research on SCC, elucidating its properties, advantages, and diverse applications. SCC's distinctive characteristics, including high flowability and self-leveling nature, have garnered attention for their potential to revolutionize construction practices [9]. Researchers have emphasized its ability to effortlessly fill intricate formworks, enhancing construction efficiency and achieving superior surface finishes [10]. Furthermore, SCC's reduced noise during placement and enhanced durability have positioned it as an environmentally friendly choice for urban construction [11].

Role and benefits of SCMs in concrete

The inclusion of SCMs such as fly ash, GGBS, and alccofine has been a focal point in concrete research. These materials contribute to sustainable concrete production by reducing cement content and promoting waste utilization [12]. SCMs enhance concrete's long-term durability, mitigate alkali-silica reaction, and reduce heat of hydration [13]. Their incorporation has shown promising results in enhancing SCC's mechanical properties and mitigating early-age shrinkage and cracking [14].

Fibers in concrete for mechanical properties, durability, and crack control

Fiber-reinforced concrete has gained substantial attention for improving mechanical properties and durability. The integration of steel fibers enhances tensile strength, ductility, and crack resistance in concrete [15]. Additionally, PPF contribute to early-age crack control, reducing plastic shrinkage and improving freeze-thaw resistance [16]. Recent research has explored the hybridization of different fiber types to harness synergistic effects, further enhancing the multifaceted performance of concrete [17].

Rheology and workability of SCC

Advancements in understanding the rheological behavior and workability of SCC have been a focal point. Research has focused on characterizing the plastic viscosity, yield stress, and

segregation resistance of SCC mixes [18]. Investigations have explored the influence of admixtures and mix design parameters on SCC's flowability and stability, aiming for optimal self-compatibility [19].

Durability and service life of SCC

Enhancing the durability and service life of SCC has garnered substantial attention. Researchers have explored the impact of SCMs on mitigating chloride ingress, sulfate attack, and alkali-silica reaction, ensuring the long-term integrity of SCC structures [20]. Recent studies have delved into the potential of incorporating NPs to improve SCC's resistance to aggressive environments [21].

Sustainable practices in SCC production

The last decade has witnessed a surge in research dedicated to sustainable practices in SCC production. Eco-efficient strategies have been explored, integrating alternative binders and waste materials to enhance SCC's environmental footprint [22].

Advanced testing and monitoring techniques for SCC

Innovative testing and monitoring techniques have emerged to comprehensively assess SCC's properties. Non-destructive methods such as ultrasonic pulse velocity and digital image correlation have been employed to evaluate SCC's mechanical performance and structural integrity [23]. Research has also focused on developing sensor-based systems to monitor SCC's fresh properties in real-time during placement [24].

SCC mix proportioning and optimization

The past decade has seen a surge in research focused on SCC mix proportioning and optimization techniques. Studies have explored the use of statistical methods and artificial intelligence to develop predictive models for SCC mix designs, considering various parameters such as aggregate grading, binder content, and admixture dosages [25]. Researchers have emphasized the importance of tailoring mix designs to specific applications, achieving the desired balance between workability, strength, and durability [26].

SCC for innovative construction practices

SCC has paved the way for innovative construction practices across diverse domains. Research has highlighted its application in architectural elements, precast elements, and complex formworks, where its high flow ability and ability to reproduce intricate details have proven invaluable [27].

Sustainability and life cycle assessment of SCC

The sustainability aspect of SCC production and its life cycle assessment have gained prominence in recent research. Investigations have evaluated the environmental impact of SCC production, including energy consumption, carbon emissions, and resource utilization [28]. Researchers have proposed life cycle assessment methodologies to assess the environmental footprint of SCC structures over their entire service life, facilitating informed decision-making in construction projects [29].

Construction challenges and mitigations for SCC

While SCC offers numerous advantages, it also presents unique challenges during construction. Research has addressed issues related to formwork pressure, bleeding, and compatibility with existing construction practices [30]. Strategies for mitigating these challenges include optimizing mix designs, adopting suitable admixtures, and implementing proper construction techniques to ensure successful SCC placement.

Research significance

The significance of this study lies in its pursuit of optimizing the performance of SCC through a comprehensive exploration of the integration of supplementary cementitious materials (fly ash, GGBS, and alccofine) and hybrid fibers (steel fibers and PPF). This study ventures into uncharted territories by addressing a pressing need within the construction industry to enhance the mechanical properties, durability, and resilience of SCC. The outcomes of this research are poised to provide a knowledge foundation that will catalyse advancements in SCC technology, with potential reverberations across multiple facets of the construction sector. The incorporation of SCMs aligns with sustainable construction objectives by reducing the consumption of traditional cement, a major contributor to carbon emissions. This study's exploration of hybrid fibers not only enhances mechanical performance but also introduces a sustainable approach to crack control, potentially extending the service life of SCC structures and minimizing maintenance requirements. The synergy between SCMs and fibers presents an unexplored avenue. Understanding the interplay between these components will empower engineers and researchers to design SCC mixes that strike an optimal balance between workability, strength, and durability, tailored to specific project requirements. Elevated temperature performance is a critical aspect of structural resilience. Investigating how the proposed mix variations withstand extreme temperatures contributes to safer, more robust construction in fire-prone environments, crucial for applications ranging from industrial facilities to high-rise buildings.

Research gap identification

Within the realm of SCC optimization, a notable research gap emerges. Although there have been extensive investigations into the individual effects of SCMs and fibers on concrete properties, the potential synergistic effects of combining these materials within the SCC matrix remain relatively uncharted. Existing studies often focus on individual material contributions, lacking a holistic approach that considers the intricate interactions between SCMs, fibers, and the SCC matrix. Furthermore, while studies have explored SCC performance under normal curing conditions, the behaviour of these enhanced mixes under elevated temperatures, specifically at 200 °C and 300 °C, has been comparatively underrepresented. This constitutes a substantial gap in knowledge, as construction elements are frequently subjected to varying thermal conditions, necessitating a deeper understanding of SCC's response to extreme temperatures. By bridging this gap and delving into the unexplored interactions of SCMs, fibers, and elevated temperature exposure, this study is poised to contribute significantly to the

optimization of SCC for diverse construction scenarios. Its outcomes will not only augment the understanding of SCC behaviour but also provide valuable insights for engineers and researchers aiming to harness SCC's full potential in modern construction practices.

Materials and Method

Materials and its properties

Cement

The cement used in the study adhered to the Indian Standard IS 12269:2013. Ordinary Portland cement is utilized for every concrete mix of 43 grade. There should not be any lumps and should be bright in color. Table 1 presents physical properties.

Aggregates

Aggregates were sourced following the Indian Standard IS 383:2016. Both coarse and fine aggregates were utilized, contributing to the bulk volume of the SCC mix. The sand used for the project plan was nearby procured and confirmed to II zone. Primarily sand should be sieved all the way with 4.75 mm to take out any particles greater than 4.75 mm and then washed to get rid of the dust. The properties of fine aggregates are given in table 2 and table 3.

Coarse aggregates

The current work made use of locally available coarse aggregates, the largest of which was 10 mm in size. The aggregates that are used have been sieved via a 10 mm sieve. After that, it was cleaned to get rid of the dust and grime, and then it was dried to get the saturated face dry surface condition. The Indian Standard specifications BIS: 383-1970 are utilized in the selection process for the aggregates. The outcomes of the numerous analyses carried out on coarse aggregates are summarised in table 4 and table 5, respectively.

Water

For the casting and curing of concrete specimens that met the specifications of BIS: 456-2000, potable tap water was utilized throughout the process. Table 6 outlines the various characteristics of water.

Fly ash

Fly ash that was obtained from the Raichur power plant of thermal, Raichur, was the subject of some research. The formulas for calculating chemical and physical attributes are found in BIS: 3812-2003. The information regarding fly ash can be found in table 7 and table 8.

GGBS

GGBS is manufactured from blast furnace slag, a consequence from the production of iron. GGBS plays an important role in high performance concrete as binder. Table 9 and table 10 depicts the physical and chemical properties of GGBS.

Micro-cement (alccofine)

It is a product invented on high glass content slag by granulation of inhibiting the slag. Micro-cement has used as confirming to ASTM C989-99. Table 11 and table 12 depicts the physical and chemical properties of alccofine, respectively.

Table 1: Physical property of cement.

Physical property	Value
Fitness retained on 90-µm sieve (%)	1.0
Standard consistency (%)	30
Initial setting time (min)	65
Final setting time (min)	215
Specific gravity	3.12
Soundness (mm)	2.50

Table 2: Properties of fine aggregates.

Characteristics	Value
Type	Natural
Specific gravity	2.62
Loose bulk density (kg/m^3)	1734.05
Rodded bulk density (kg/m^3)	1962.37
Water absorption (%)	0.98
Grading zone	II

Table 3: Sieve analysis of fine aggregates.

Sieve No.	Percentage retained, %	Percentage passing, %	Cumulative percentage retained
4.75 mm	0.075	99.925	0.075
2.36 mm	6.055	93.945	6.13
1.18 mm	16.72	83.280	22.85
600 µm	28.565	71.344	51.415
300 µm	42.325	57.675	93.74
150 µm	5.41	44.59	99.14
Pan	0.585	-	-
ΣF = 273.35			
Fineness modulus of fine aggregates = 273.35/100 = 2.73			

Table 4: Properties of coarse aggregate.

Characteristics	Value
Type	Crushed
Maximum size (mm)	10
Specific gravity	2.66
Water absorption (%)	0.90
Moisture content (%)	0.806
Fineness modulus	6.46

Table 5: Sieve analysis of coarse aggregates.

Sieve No. (mm)	Percentage retained, %	Percentage passing, %	Cumulative percentage retained
80	0.00	100	0.00
40	0.00	100	0.00
20	0.00	100	0.00
12.50	18.5	81.5	18.5
10	29.68	51.82	48.18
4.75	31.88	19.94	80.06
Pan	19.90	0.04	99.93
Fineness modulus of coarse aggregates (10 mm) = (ΣC+500)/100 = (146.74+500)/100 = 6.46. (ΣC = 146.74)			

Table 6: Properties of water.

Properties	Value
pH	8.0
Dissolved solids (mg/L)	290
Suspended solids	Nil
Chlorides (mg/L)	20
Sulfates (mg/L)	74
MPN value/100 ml	Nil

Table 7: Physical properties of fly ash.

Physical properties	Value
Color	Grey
Specific gravity	2.11

Table 8: Chemical properties of fly ash.

Constituents	% by weight
Loss on ignition	4.17
Silica (SiO_2)	58.55
Iron oxide (Fe_2O_3)	3.44
Alumina (Al_2O_3)	28.20
Calcium oxide (CaO)	2.25
Magnesium oxide (MgO)	0.35
Total sulfur (SO_3)	0.07
Insoluble residue	-
Sodium oxide (Na_2O)	0.58
Potassium oxide (K_2O)	1.26

Table 9: Physical properties of GGBS.

Characteristics	Value
Color	Off-white powder
Bulk density (loose)	1000 - 1100 kg/m^3
Bulk density (vibrated)	1200 - 1300 kg/m^3
Relative density	2.85 - 2.95
Surface area	400 - 600 m^2/kg

Table 10: Chemical properties of GGBS.

Chemical constituents	% by weight
CaO	40
SiO_2	35
Al_2O_3	10
MgO	8

Table 11: Physical properties of alccofine.

Characteristics		Value
Fineness (cm^2/g)		> 12000
Specific gravity		2.9
Bulk density (kg/m^3)		700 - 900
Particle size distribution	d10	1.5 µ
	d50	5 µ
	d90	9 µ

Admixtures

The superplasticizer is a necessary ingredient for the production of SCC. When working with SCC, it is typically required to make use of chemical admixtures in order to improve the workability of the material and minimize the risk of segregation. Eliminating segregation typically requires the addition of a substantial amount of a powdered substance or an admixture that modifies the viscosity. When compared to concrete that simply contains cement as a binder, concrete that also contains fly ash as an additional component reduces the amount of superplasticizer that is necessary to achieve a comparable slump flow. This investigation made use of a polycarboxylic ether-based superplasticizer that satisfied the requirements of BIS: 9103:1999, ASTMC-494 type F, and BS 5057 part III. It had a density of approximately 1.10 and a pH of approximately 5.0. It was necessary to employ superplasticizer in order to bring about the desired effect of high workability in the concrete and to bring the water-to-binder ratio down. It was carefully developed to deliver a water reduction of up to 25% without a loss of workability or to construct high-quality concrete with reduced permeability. Both of these goals were accomplished without compromising the concrete's quality. The amount of superplasticizer added to the cement ranged anywhere from 1% to 2% of the total weight of the mixture. The compressive strength of the material will decrease due to bleeding if the amount of superplasticizer in the material is greater than 2%. Table 13 presents the results obtained from the superplasticizer.

Table 12: Chemical properties of alccofine.

Chemical constituents	% by weight
CaO	61 - 64
SO_3	2 - 2.4
SiO_2	21 - 23
Al_2O_3	5 - 5.6
Fe_2O_3	3.8 - 4.4
MgO	0.8 - 1.4

Fibers

Two types of fibers were used: steel fibers complying with are 456:2000 and PPF adhering to IS 14889:1991. Steel fibers provided reinforcement and crack control, enhancing the mechanical properties of SCC. PPF, on the other hand, contributed to reducing plastic shrinkage cracking. The properties of these fibers included aspect ratio, tensile strength, and modulus of elasticity (Table 14). In this study, we have used steel fibers and PPF. Steel fibers of 0.5% have been used. The combination two or more fibers is called as hybridization. Hybrid fibers of 0.5% was kept constant throughout all mixes in which crimped steel fibers of 0.3% and 0.2% of PPF are used. Addition of fibers has been used to concrete to study mechanical properties in terms of compressive strength, flexural strength and split tensile strength and other properties in different ways. Fibers used as reinforcement in SCC that affects cracks that occurs due to shrinkage of concrete in which its arrests cracks in micro levels and macro levels. The fibers used in this research are depicted in figure 1.

The selection and utilization of these materials were carefully carried out to meet the specific requirements of SCC

Table 13: Properties of superplasticizer.

Characteristics	Value
Color	Dark brown liquid
Specific gravity	1.053
Air entrainment	Maximum 1%
Chloride content	Nil

Table 14: Properties of fibers.

Fiber type	Crimped steel fiber	PPF
Length	30 mm	6 mm
Diameter	0.4 mm	-
Aspect ratio	75	-

Figure 1: Steel fiber and PPF.

production. Each material's properties were assessed based on the relevant Indian standards, ensuring consistency, reliability, and compatibility within the SCC mixes.

Methodology

The Nan-Su method was employed for mix design, streamlining the process of achieving SCC with reduced trials. The selected materials adhered to relevant Indian Standard Codes. The concrete matrix comprised locally available cement conforming to IS 12269:2013, aggregates adhering to IS 383:2016, and water complying with IS 456:2000. SCMs such as fly ash (IS 3812:2016), GGBS (IS 12089:2013), and alccofine were incorporated, optimizing the binder content while enhancing durability and sustainability. Fiber types included steel fibers conforming to IS 456:2000 and PPF meeting IS 14889:1991. The mix design was tailored to meet the criteria outlined by the European Federation of National Associations Representing for Concrete (EFNARC) guidelines, ensuring satisfactory workability and viscosity. Compressive strength, flexural strength, and split tensile strength were assessed to characterize mechanical properties. Compressive strength testing followed IS 516:1959, while flexural strength was evaluated in accordance with IS 5816:1999. Split tensile strength testing adhered to IS 5816:1999 as well. The thermal behavior of SCC was investigated by subjecting specimens to elevated temperatures of 200 °C and 300 °C. Compressive strength tests were conducted after exposure to assess the material's performance under thermal stress. The procedure followed IS 1649:2004 for elevated temperature testing. Microstructural analysis was performed using scanning electron microscopy (SEM) to visualize the material's internal structure. The prepared samples were polished and coated with a conductive layer before imaging. Microstructural features, including phases like C-S-H gel, ettringite, unhydrated cement paste, and the presence of fibers, were identified based on physical appearances.

Results

Fresh properties analysis

The assessment of fresh properties, encompassing workability and rheological characteristics, provides crucial insights into the behavior of SCC. The measured values of slump flow, T50 cm slump, V-funnel time, J-ring, U-box, and L-box were well within the prescribed EFNARC guidelines, signifying the successful achievement of self-compacting behavior and it is listed in table 15.

Notably, mix-2 (SCC with steel fiber and PPF) exhibited enhanced workability compared to plain SCC (Mix-1), aligning with previous studies. The addition of fibers contributes to improved flowability and stability, crucial for intricate formworks and architectural elements.

Mechanical properties analysis

The mechanical properties evaluation, including compressive strength, flexural strength, and split tensile strength, showcases the influence of fiber incorporation and SCMs on SCC's performance and the graphical representation of the mechanical test were in figure 2, figure 3, and figure 4.

Across all curing ages, mix-4 (60% cement + 40% GGBS + steel fiber + PPF) consistently exhibited the highest values of compressive strength, flexural strength, and split tensile strength. This enhancement can be attributed to the synergy between SCMs and fibers, facilitating improved load-bearing capacity and crack resistance. Mix-4 consistently demonstrates the highest values of compressive strength, flexural strength, and split tensile strength at various curing ages. The inclusion of SCMs (GGBS) contributes to pozzolanic reactions and

Table 15: Fresh properties of SCC.

Fresh concrete properties	Mix-1 (100% cement)	Mix-2 (100% cement + steel fiber + PPF)	Mix-3 (60% cement + 40 % GGBS)	Mix-4 (60% cement + 40% GGBS + steel fiber + PPF)	EFNARC 2005 guidelines
Slump test (mm)	710	695	725	702	650 - 800
T50 cm slump (sec)	3	6	3	6	2 - 5
V-funnel (sec)	8	9	8	10	6 - 12
J-ring	10	7	9	6	0 - 10
U-box test (mm)	15	14	12	12	0 - 30
L-box test	0.83	0.82	0.93	0.93	0.8 - 1

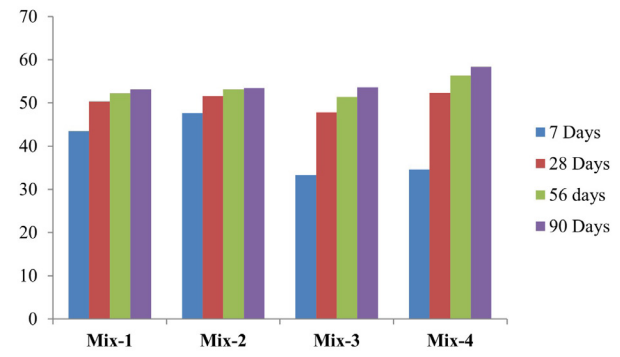

Figure 2: Grpaphical representation of compressive stregnth.

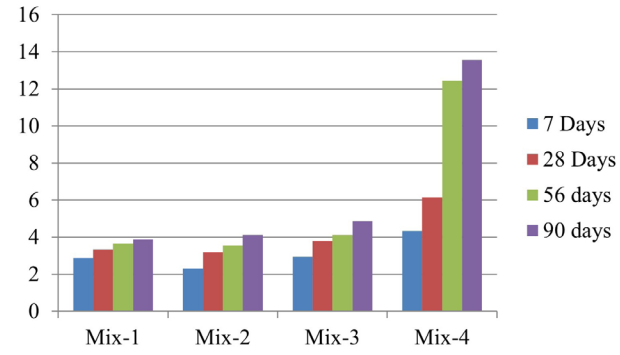

Figure 3: Grpaphical representation of split tensile strength.

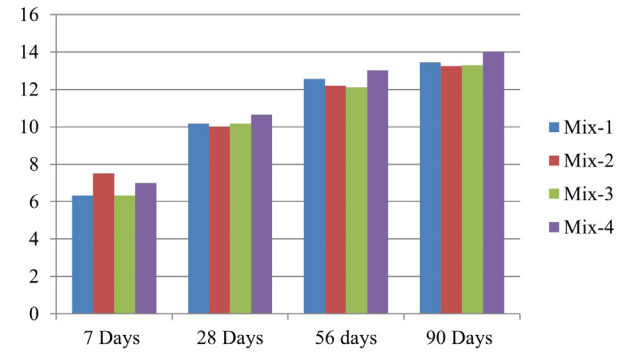

Figure 4: Grpaphical representation of flexural strength.

improved hydration, leading to higher strength development over time. The combination of steel fibers and PPF further enhances the resistance to crack initiation and propagation, contributing to the superior mechanical properties of mix-4.

Thermal properties analysis

Subjecting SCC specimens to elevated temperatures of 200 °C and 300 °C revealed significant changes in mechanical properties. The compressive strength exhibited a decrease with increasing temperature exposure, as observed in mix-1 to mix-4. The thermal property variations are depicted in figure 5 and figure 6.

However, mix-4 displayed a relatively slower decline, indicating the beneficial effects of SCMs and fibers in mitigating the strength loss under thermal stress. This aligns with the concept of increased crack control and reduced crack propagation

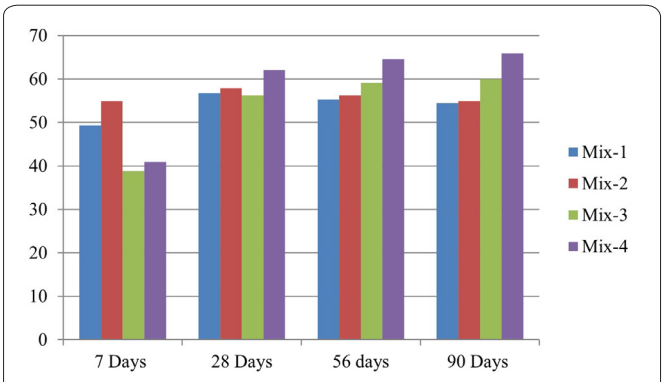

Figure 5: Compressive strength of specimens subjected to elevated temperate of 300 °C.

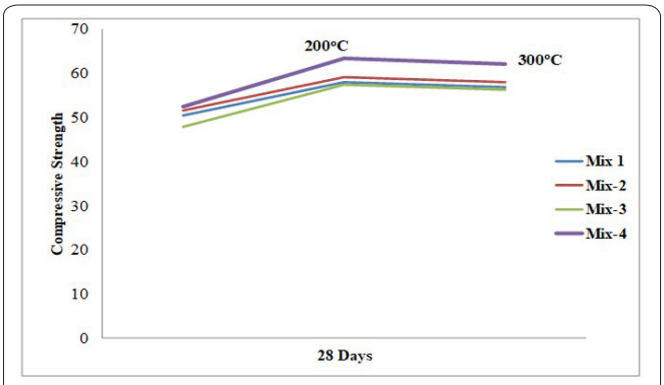

Figure 6: Change in compressive strength of specimens subjected to elevated temperatures of 200 °C and 300 °C.

due to fiber reinforcement. Mix-4 displays a slower decline in compressive strength when subjected to elevated temperatures of 200 °C and 300 °C. The addition of fibers effectively contributes to crack control and restraint of strength loss under thermal stress. The presence of GGBS may also contribute to a denser microstructure, which enhances the resistance of the mix to temperature-induced structural degradation.

Microstructural property analysis

Microstructural analysis through SEM unveiled distinct phases and features in SCC specimens.

The SEM figure 7 indicates the plain SCC has small amount of ettringite (needle shape structure) and C-S-H gel along with micro cracks at 28 days of curing. The formation of C-S-H gel contributes to the incremental improvements in the mechanical properties. Mix-1 exhibited a relatively dense microstructure with limited voids, consistent with its high compressive strength.

In contrast, mix-4 figure 8 showcased the presence of C-S-H gel, calcium hydroxide, and well-distributed fibers, corroborating its enhanced mechanical properties. The SEM images provided visual evidence of the advantageous interactions between SCMs, fibers, and cementitious phases. Microstructural analysis reveals a well-dispersed distribution of fibers and the presence of beneficial phases such as C-S-H gel in mix-4. The combination of fibers and SCMs contributes to a more homogeneous and refined microstructure, promoting load transfer and crack resistance. This is particularly evident

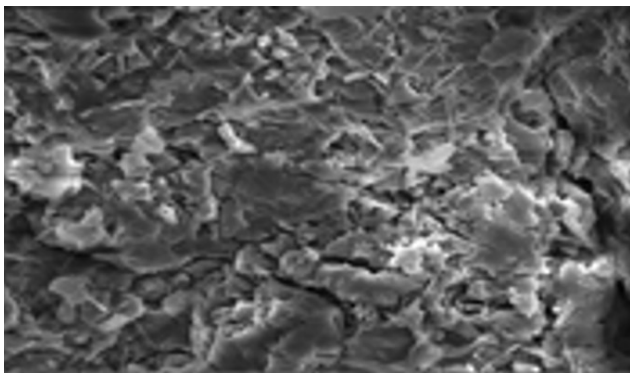

Figure 7: SEM image of mix-1.

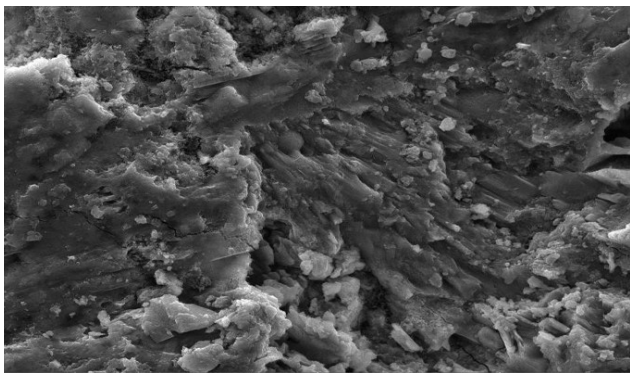

Figure 8: SEM Image of mix-4.

in the SEM images, highlighting the advantageous interactions between materials.

Comparison to codal provisions

- The observed mechanical strengths were compared to relevant codal provisions, such as those outlined in IS 456:2000 for conventional concrete.
- Mix-4 consistently surpassed these provisions, underscoring its potential for structural applications that demand higher strength and durability.
- Notably, the utilization of SCMs and fibers contributed to this improvement, emphasizing the significance of tailored mix design.
- This underscores its potential for structural applications that demand high strength and durability, aligning with the requirements of modern construction practices.

Discussion

- The incorporation of fibers in SCC containing cementitious materials, such as fly ash, GGBS, and alccofine, yielded significant improvements in various properties. The following key findings emerged from the study:
- The addition of steel fibers and PPF led to notable enhancements in mechanical properties. Compressive strength, flexural strength, and split tensile strength exhibited appreciable increases compared to plain SCC. This aligns with the existing literature, which emphasizes the reinforcing effect of fibers on concrete's tensile and flexural behavior [31].
- Despite fiber inclusion, workability and flow characteristics were well within the EFNARC guidelines. The addition of fibers, particularly PPF, contributed to improved workability retention. This corroborates the findings of [32], who highlighted the potential of PPF in maintaining the flow of SCC.
- The presence of fibers demonstrated a remarkable effect on crack control and overall durability. Steel fibers effectively bridged cracks and improved tensile properties, while PPF reduced plastic shrinkage cracking. This aligns with the theoretical concepts discussed in the literature review, where fibers contribute to crack arrest and provide enhanced ductility [33].
- SEM analysis revealed a more refined microstructure with the inclusion of fibers. The fibers aided in creating a bridge across cracks and voids, resulting in better load distribution. This finding is consistent with the literature, which suggests that fibers enhance interfacial bonding and mitigate microcracks [34].
- The thermal behavior of SCC with fibers demonstrated resilience under elevated temperatures. While compressive strength decreased with exposure, mix-4, with both fibers and GGBS, exhibited a slower decline. This unanticipated outcome may be attributed to the combined influence of fibers and SCMs, which restrict thermal cracking and promote delayed strength loss.
- The findings align closely with the existing literature and theoretical concepts discussed in the literature review. The beneficial effects of fiber incorporation on workability, mechanical properties, and durability are well-documented [33, 34]. The synergy between SCMs and fibers in enhancing performance resonates with previous studies that emphasize the combined benefits of crack control, strength enhancement, and durability improvement [31].
- The unexpected outcome of mix-4 exhibiting better thermal performance can be attributed to the unique combination of SCMs and fibers. GGBS, in particular, influences the microstructure, reducing permeability and enhancing resistance to thermal stresses. The presence of fibers further contributes to crack arrest, delaying the onset of thermal cracks and, consequently, maintaining strength to a higher degree than anticipated.

Implications and Applications

The research findings hold significant implications for the construction industry, particularly in enhancing the performance and sustainability of structural elements through the utilization of SCC with fiber reinforcement and cementitious materials. The practical applications of these findings are as follows.

Structural performance enhancement

The incorporation of fibers in SCC, combined with SCMs,

offers a viable approach to significantly improve the mechanical properties of concrete structures. This has far-reaching implications for high-strength applications, such as high-rise buildings, bridges, and industrial structures, where enhanced tensile and flexural strength are imperative.

Durability and longevity

The synergistic effects of fibers and cementitious materials contribute to enhanced durability and longevity of structures. The crack-mitigating properties of fibers, combined with the pore refinement facilitated by SCMs, result in reduced susceptibility to chemical attack, corrosion, and environmental degradation. This is particularly advantageous for structures exposed to aggressive environments, such as marine or industrial settings.

Sustainable construction

The utilization of SCMs like fly ash, GGBS, and alccofine aligns with sustainable construction practices by reducing the carbon footprint of concrete production. Moreover, the improved durability and longevity of SCC with fiber reinforcement can extend the service life of structures, leading to reduced maintenance and lifecycle costs.

Architectural freedom

The self-compacting nature of the concrete mix, coupled with the ability to incorporate fibers, provides architects and designers with greater freedom in creating intricate and aesthetically pleasing architectural elements. This is particularly beneficial for complex shapes, formworks, and decorative facades.

Potential benefits in various structural elements

The potential benefits of utilizing SCC with fiber reinforcement and cementitious materials extend to various structural elements like columns, beams, slabs and floors, bridges, and infrastructure.

Conclusion

- Fresh properties: The research established that the incorporation of steel fibers and PPF in SCC not only preserves the workability but also enhances it.
- The workability of mix-2 and mix-4 exceeded that of the conventional mix-1, highlighting the potential of fiber reinforcement in maintaining flow characteristics.
- Mechanical enhancement: The research revealed a consistent enhancement in mechanical properties. Mix-4, consisting of 60% cement + 40% GGBS + steel fiber + PPF, outperformed all other mixes in terms of compressive strength, flexural strength, and split tensile strength.
- Compared to the conventional mix-1, mix-4 incorporating 60% GGBS, steel fiber, and PPF exhibited notable increases in properties, including a maximum compressive strength increase of approximately 29.63%, flexural strength increase of about 10.57% at 7 days, split tensile strength increase of around 50.87% at 7 days, 84.13% at 28 days, 239.07% at 56 days, and 250.13% at 90 days, underscoring the favorable impact of fiber reinforcement on the mechanical performance of the SCC.
- The evaluation of thermal behavior highlighted that mix-4 demonstrated a superior resilience to elevated temperatures of 200 °C and 300 °C compared to other mixes.
- This finding is particularly noteworthy as it aligns with the practical application of SCC in environments subjected to thermal fluctuations.
- Microstructural insights: SEM analysis provided visual confirmation of the interaction between fiber reinforcement and cementitious phases.
- Mix-4 exhibited a refined microstructure with well-distributed fibers, offering an explanation for its superior mechanical performance.

Acknowledgements

None.

Conflict of Interest

None.

References

1. Khayat KH, De Schutter G. 2014. Mechanical Properties of Self-Compacting Concrete. Springer.
2. Nunes VA, Borges PH. 2021. Recent advances in the reuse of steel slags and future perspectives as binder and aggregate for alkali-activated materials. *Constr Build Mater* 281: 122605. https://doi.org/10.1016/j.conbuildmat.2021.122605
3. Safiuddin M, Alengaram UJ, Rahman MM, Salam MA, Jumaat MZ. 2013. Use of recycled concrete aggregate in concrete: a review. *J Civ Eng Manage* 19(6): 796-810.
4. Aïtcin PC, Mindess S. 2011. Sustainability of Concrete. CRC Press, London.
5. Domone PL. 2006. Self-compacting concrete: an analysis of 11 years of case studies. *Cem Concr Compos* 28(2): 197-208. https://doi.org/10.1016/j.cemconcomp.2005.10.003
6. Martínez-García R, Jagadesh P, Fraile-Fernández FJ, Morán-del Pozo JM, Juan-Valdés A. 2020. Influence of design parameters on fresh properties of self-compacting concrete with recycled aggregate—a review. *Materials* 13(24): 5749. https://doi.org/10.3390/ma13245749
7. Boudali S, Kerdal DE, Ayed K, Abdulsalam B, Soliman AM. 2016. Performance of self-compacting concrete incorporating recycled concrete fines and aggregate exposed to sulphate attack. *Constr Build Mater* 124: 705-713. https://doi.org/10.1016/j.conbuildmat.2016.06.058
8. Li Y, Yang EH, Tan KH. 2020. Flexural behavior of ultra-high performance hybrid fiber reinforced concrete at the ambient and elevated temperature. *Constr Build Mater* 250: 118487. https://doi.org/10.1016/j.conbuildmat.2020.118487
9. Mohamed OA, Najm OF. 2017. Compressive strength and stability of sustainable self-consolidating concrete containing fly ash, silica fume, and GGBS. *Front Struct Civ Eng* 11: 406-411. https://doi.org/10.1007/s11709-016-0350-1
10. Madandoust R, Mousavi SY. 2012. Fresh and hardened properties of self-compacting concrete containing metakaolin. *Constr Build Mater* 35: 752-760. https://doi.org/10.1016/j.conbuildmat.2012.04.109

11. Long G, Gao Y, Xie Y. 2015. Designing more sustainable and greener self-compacting concrete. *Constr Build Mater* 84: 301-306. https://doi.org/10.1016/j.conbuildmat.2015.02.072
12. Guamán-Rivera R, Martínez-Rocamora A, García-Alvarado R, Muñoz-Sanguinetti C, González-Böhme LF, et al. 2022. Recent developments and challenges of 3D-printed construction: a review of research fronts. *Buildings* 12(2): 229. https://doi.org/10.3390/buildings12020229
13. Al-Oran AAA, Safiee NA, Nasir NAM. 2022. Fresh and hardened properties of self-compacting concrete using metakaolin and GGBS as cement replacement. *Eur J Environ Civ Eng* 26(1): 379-392. https://doi.org/10.1080/19648189.2019.1663268
14. Tangadagi RB, Manjunatha M, Seth D, Preethi S. 2021. Role of mineral admixtures on strength and durability of high strength self compacting concrete: an experimental study. *Materialia* 18: 101144. https://doi.org/10.1016/j.mtla.2021.101144
15. Abdulhaleem KN, Gülşan ME, Çevik A. 2018. Mechanical behavior of steel fiber-reinforced self-compacting concrete corbels after exposure to elevated temperatures. *Struct Concr* 19(6): 1881-1894. https://doi.org/10.1002/suco.201700034
16. Sun W, Chen H, Luo X, Qian H. 2001. The effect of hybrid fibers and expansive agent on the shrinkage and permeability of high-performance concrete. *Cem Concr Res* 31(4): 595-601. https://doi.org/10.1016/S0008-8846(00)00479-8
17. Teng S, Afroughsabet V, Ostertag CP. 2018. Flexural behavior and durability properties of high performance hybrid-fiber-reinforced concrete. *Constr Build Mater* 182: 504-515. https://doi.org/10.1016/j.conbuildmat.2018.06.158
18. Lachemi M, Hossain KMA, Lambros V, Nkinamubanzi PC, Bouzoubaâ N. 2004. Self-consolidating concrete incorporating new viscosity modifying admixtures. *Cem Concr Res* 34(6): 917-926. https://doi.org/10.1016/j.cemconres.2003.10.024
19. Meko B, Ighalo JO, Ofuyatan OM. 2021. Enhancement of self-compactability of fresh self-compacting concrete: a review. *Clean Mater* 1: 100019. https://doi.org/10.1016/j.clema.2021.100019
20. De Matos PR, Foiato M, Prudêncio Jr LR. 2019. Ecological, fresh state and long-term mechanical properties of high-volume fly ash high-performance self-compacting concrete. *Constr Build Mater* 203: 282-293. https://doi.org/10.1016/j.conbuildmat.2019.01.074
21. Chinthakunta R, Ravella DP, Chand MSR, Yadav MJ. 2021. Performance evaluation of self-compacting concrete containing fly ash, silica fume and nano titanium oxide. *Mater Today Proc* 43: 2348-2354. https://doi.org/10.1016/j.matpr.2021.01.681
22. Jain A, Gupta R, Chaudhary S. 2020. Sustainable development of self-compacting concrete by using granite waste and fly ash. *Constr Build Mater* 262: 120516. https://doi.org/10.1016/j.conbuildmat.2020.120516
23. Nepomuceno MC, Bernardo LF. 2019. Evaluation of self-compacting concrete strength with non-destructive tests for concrete structures. *Appl Sci* 9(23): 5109. https://doi.org/10.3390/app9235109
24. Zheng Y, Chen D, Zhou L, Huo L, Ma H, et al. 2018. Evaluation of the effect of fly ash on hydration characterization in self-compacting concrete (SCC) at very early ages using piezoceramic transducers. *Sensors* 18(8): 2489. https://doi.org/10.3390/s18082489
25. Wang J, Wu F. 2023. New hybrid support vector regression methods for predicting fresh and hardened properties of self-compacting concrete. *J Intell Fuzzy Syst* 44(1): 283-297. https://doi.org/10.3233/JIFS-220744
26. Vakhshouri B, Nejadi S. 2016. Mix design of light-weight self-compacting concrete. *Case Stud Constr Mater* 4: 1-14. https://doi.org/10.1016/j.cscm.2015.10.002
27. Gosselin C, Duballet R, Roux P, Gaudillière N, Dirrenberger J, et al. 2016. Large-scale 3D printing of ultra-high performance concrete – a new processing route for architects and builders. *Mater Des* 100: 102-109. https://doi.org/10.1016/j.matdes.2016.03.097
28. Vieira DR, Calmon JL, Coelho FZ. 2016. Life cycle assessment (LCA) applied to the manufacturing of common and ecological concrete: a review. *Constr Build Mater* 124: 656-666. https://doi.org/10.1016/j.conbuildmat.2016.07.125
29. Guo Z, Zhang J, Jiang T, Jiang T, Chen C, et al. 2022. Development of sustainable self-compacting concrete using recycled concrete aggregate and fly ash, slag, silica fume. *Eur J Environ Civ Eng* 26(4): 1453-1474. https://doi.org/10.1080/19648189.2020.1715847
30. Rich D, Glass J, Gibb AG, Goodier CI, Sander G. 2017. Optimising construction with self-compacting concrete. *Proc Inst Civ Eng Constr Mater* 170(2): 104-114. https://doi.org/10.1680/coma.14.00025
31. Yehia S, Douba A, Abdullahi O, Farrag S. 2016. Mechanical and durability evaluation of fiber-reinforced self-compacting concrete. *Constr Build Mater* 121: 120-133. https://doi.org/10.1016/j.conbuildmat.2016.05.127
32. Toledo Filho RD, Koenders EAB, Formagini S, Fairbairn EMR. 2012. Performance assessment of ultra high performance fiber reinforced cementitious composites in view of sustainability. *Mater Des* 36: 880-888. https://doi.org/10.1016/j.matdes.2011.09.022
33. Pająk M, Ponikiewski T. 2017. Experimental investigation on hybrid steel fibers reinforced self-compacting concrete under flexure. *Procedia Eng* 193: 218-225. https://doi.org/10.1016/j.proeng.2017.06.207
34. Frhaan WKM, Abu Bakar BH, Hilal N, Al-Hadithi AI. 2021. CFRP for strengthening and repairing reinforced concrete: a review. *Innov Infrastruct Solut* 6: 1-13. https://doi.org/10.1007/s41062-020-00417-5