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REVIEW PAPER

Self-Compacting Concrete Using Supplementary Cementitious Materials and Fibers: Review

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Abstract

This research paper undertook a methodical examination of existing literature concerning self compacting concrete (SCC) properties using supplementary cementitious materials (SCMs) other than habitual materials according to the latest survey. From a sustainability perspective, habitual SCMs have taken the place of cement. However, because habitual SCM are heavily exploited and in short supply, current researchers are focusing more on the latest industrial waste, construction and demolition waste, and natural by-products. The present period places greater emphasis on fiber-reinforced SCC but knowledge of the use of different types of fibers and their application in SCC according to their volume fraction, aspect ratio, and distribution is presented for enhancing the microstructure, fresh, mechanical, and durability properties. Works of literature focus on the impact of fibers of metallic, non-metallic, synthetic, and natural fibers in mono and hybrid combinations. The results reported by several authors were illustrated in tables and figures to gain knowledge on the limitations of using contemporary SCMs on fresh, mechanical, durability, and microstructure properties of SCC. From the literature outcomes, the suitable contemporary SCMs as an optimal powder content by the replacement of cement for a maximum extent in SCC as binary and ternary blended forms were reviewed to reduce the carbon dioxide emissions in the atmosphere during the SCC production process that maintains sustainability. Further, the addition of synthetic fibers and metallic/non-metallic fibers were exploited to a maximum extent for enhancing the tensile and flexural behaviour of SCC which could be overcome by the adoption of natural fibers as mono/hybrid fiber additions along with metallic/non-metallic/synthetic fibers combinations as self-treatments to prevent the degradation of natural fibers when added in SCC would influence as cutting-edge materials to create a sustainable environment. Hence, the future scope is the incorporation of novel SCMs based on the tailor-made constituents of chemical composition with the addition of treated natural fibers in preparation for greener SCC.

Keywords Self-compacting concrete · SCM · Fibers · Fresh properties · Mechanical properties · Durability · Microstructure · Computational fluid dynamics

1 Introduction

Recent events have led to the adoption of several types of special concrete in the building sector as well as their development at the research level. One such type is Rheodynamic concrete which falls under the category of high-performance concrete at its initial stages, introduced in Japan in 1980 and developed by Hajime Okamura and Ozawa who labelled it as SCC (Hajime and Masahiro 2003). It's a traditional concrete that replaces mechanical vibration with a natural gravitational force because of high fluidity and moderate viscosity.

Sustainability is a vital term to curtail the overexploitation of natural renewable resources namely fine aggregates, coarse aggregates, and raw materials used for the manufacture of cement in the production of concrete. For the sustainability of the construction sector, the waste management principle of reduce, reuse, and recycle (RRR) could be formulated that reflects social, environmental, and economic pillars globally. In the construction industry, this was achieved by reducing the energy for concrete production through major constituents employed, reuse of industrial by-products, reduction of carbon dioxide emissions, adoption of low-cost construction materials, etc.

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Sustainable indicators were assessed in terms of prime factors namely environmental, functional, and economic for the concrete when cement was replaced by supplementary cementitious materials (SCMs) Viz. fly ash (FA), ground granulated blast furnace slag (GGBS), and silica fume (SF). The fifteen sustainable indicators were examined and found that 40% GGBS as a substitute for cement was regarded as a sustainable mix amongst other mixes that were developed. It was reported that SCMs: FA, GGBFS and SF as a replacer for ordinary Portland cement (OPC) had reduced embodied energy and CO_2 emissions curtailed by 1640 kg, 730 kg and 760 kg respectively (Kamel et al. 2019). The SCMs namely pulverized fly ash (PFA), ground granulated blast furnace slag (GGBS), rice husk ash (RHA), and silica fume (SF) used in binary forms of concrete as a cement replacement had reflected sustainability due to the reduction of cement percentage in the production of concrete and lowered the embodied energy. The embodied CO_2 according to United Kingdom Quality Ash Association (UKQAA, 2010) for Portland Cement Type 1 CEM I: 913 kg/tonne, GGBS: 67 kg/tonne, PFA: 4 kg/tonne and Lime stone: 75 kg/tonne. The PFA as a replacer in cement reduced CO_2 emission by an average of 900 kg and in UK, the fly ash substitution in cement saved 2,50,000 tonnes of CO_2 emissions to the environment (Samada and Shahb 2017). The utilization of recycled concrete aggregate (70% RCA) along with the optimal percentage of SCMs namely fly ash (FA-20%) and SF-12% exhibited sustainability in terms of environmental, cost, and economic factors. The optimal mix of ternary blend of 20% FA + 12% SF with 70% of RCA also reduced CO_2 emissions by 0.688 (kg/kg) was reported (Maysam et al. 2023). Zhanggen et al. (2020) performed RCA with SCM combinations of FA, slag, and SF in binary, ternary, and quaternary blended combinations. The results obtained have shown improved mechanical and durability properties of SCC and are regarded as sustainable material by the reduction of cement and aggregate in the mix proportions. Hence the incorporation of industrial wastes as OPC replacement and C&D waste for aggregate replacement would decrease CO_2 emissions and carbon footprint.

It was possible to produce sustainable concrete using emerging SCMs Viz. volcanic ash, volcanic ash- limestone blend, and metakaolin-limestone blend. The strength and durability characteristics of emerging SCMs surpassed conventional SCMs excluding volcanic ash were reported (Jin-Cheng et al. 2023). The combinations of SCMs and fiber-reinforced polymer bars were reviewed and analyzed for durability issues such as alkali, chloride, sulfate attack, freeze-thaw cycles, and carbonation. Finally, the alkaline corrosion of basalt fiber reinforced polymer bars (BFRP) was overcome by carbonated SCMs leading to next-generation durable and sustainable construction materials (Xin-Lin et al. 2023). The incorporation of palm oil fuel ash as a partial substitute for cement in concrete as a sustainable SCM was reviewed through the works of literature. The review results inferred that the workability and compressive strength of concrete were improved whereas reduction in tensile strength and water absorption took place by the utilization of palm oil fuel ash (Yazan and Abu 2023). Similar research on palm oil fuel ash as a sustainable SCM was conducted review. The grinding methods were established for the raw palm oil fuel ash to fine, ultra-fine, and nanoscale that could produce high strength and offered durability resistance, the road map towards sustainable construction development (Hussein et al. 2021). The employing copper slag (CS) as a fine aggregate replacement along with SCMs FA and SF in binary and ternary blended forms as cement replacement were investigated experimentally on SCC mixes. The authors reported that key sustainable indicators namely, embodied energy and embodied CO_2 emissions were decreased when 100% of CS as a substitute for fine aggregate was conglomerated with SCMs in the ternary blended forms (60% OPC+ 30% FA+ 10% SF) of SCC. Hence for the above optimal combinations, the embodied energy and embodied CO_2 obtained was 1757.8 MJ/m^3 and 314.2 kgCO_2e/m^3 respectively (Rahul and Rizwan 2017). From the available SCMs, the choice on the selection of optimum cementitious materials for FA and GGBS as a substitute for cement from 20% to 40% with an increment of 10% was investigated through fresh, mechanical, durability, and life cycle costs by preference selection index (PSI) method. Through PSI, a sustainable performance index (SPI) was achieved and found to be superior for 40% GGBS compared to other FA and conventional SCC mixes (Suchith Reddy et al. 2020). The polyvinyl chloride waste powder (PWP) was used in SCC up to 30% along with constant SCMs of SF and GGBS mixes to arrive optimum mix based on fresh, strength and microstructure properties conducted. The authors reported that the life cycle assessment of optimum mixes (5–10% PWP) is based on the environmental impact aspects (Manjunatha et al. 2023). In SCC the manganese mine waste (MMW) was used as both aggregate replacements up to 50% and binder replacements up to 30% in binary cement replacement and ternary forms along with 20% FA. From a sustainability point of view, the cost/carbon dioxide-strength efficiency was higher for coarse aggregate replacements when compared to other mixes and conventional SCC. Hence, ternary blended SCC mixes (10% & 30% replacements) of MMW had improved flow efficiency and developed sustainability by decrease of 48% and 19% in CO_2 emissions when replaced by cement and natural aggregates respectively (Pitchiah and Arun Kumar 2024). The prospect of producing high-strength SCC using industrial copper slag of optimum 60% as a fine aggregate replacement along with 20% optimum FA has shown improved fresh, strength, and durability properties from a sustainable material perspective

(Sambangi and Eluru 2022). For the development of sustainable SCC, glass powder (GP), quartz powder (QP), and limestone powder (LP) as a partial substitute for cement up to 30% was studied for fresh and hardened properties. The mechanical properties were improved by 10% GP and 10% QP as cement replacement for HSSCC. The numerical ANN framework has shown a better correlation between the powder content and the compressive strength. Hence in SCC the utilisation of waste products by recycled process Viz. recycled GP and raw LP would result in the decrease of CO_2 emissions and the overexploitation of natural resources (Md. Munir et al. 2023). The incorporation of plastic waste as a total aggregate replacement of 50–75% had influenced acoustic and thermal insulation belonging to lightweight greener concrete adopted for non-structural components was reviewed in terms of environmental sustainability of construction (Abdulaziz et al. 2022).

In the construction engineering sector, SCC is indispensable for the growth of the current state of infrastructure today because of less need for manpower so its demand uplifts enormously. It is well known for its important properties like flowability which reveals the flow nature of paste without the need for any mechanical efforts, passing ability defines the flow of concrete between the reinforcement without any blockage and segregation resistance which maintains homogeneity while mixing, transporting, and placing in the fresh state. According to the SCC mix proportions arrived, the cement was replaced by 30% fly ash (FA) and 10% metakaolin (MK) leading to a colossal cement of 350 kg/m^3 out of total powder content of 583 kg/m^3 (Prakash et al. 2021) which impacts less on the environment as shown in Fig. 1. Ordinary Portland Cement (OPC) demands more embodied energy and is considered as the third substance on earth after steel and aluminium. One tonne of cement production yields 800 kg of CO_2 discharge and one tonne of steel production emits nearly 1.9 tonnes of CO_2. Many research works predict that the construction and operations of buildings

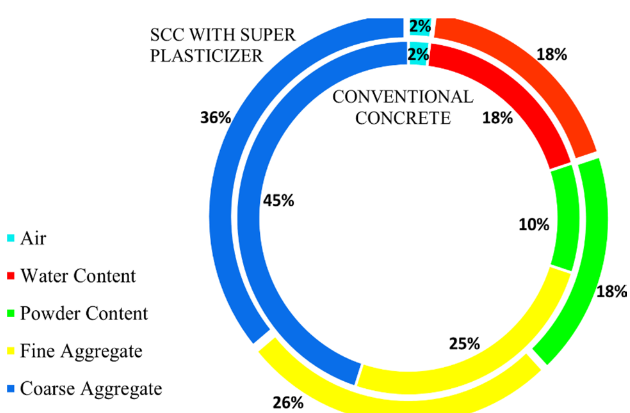


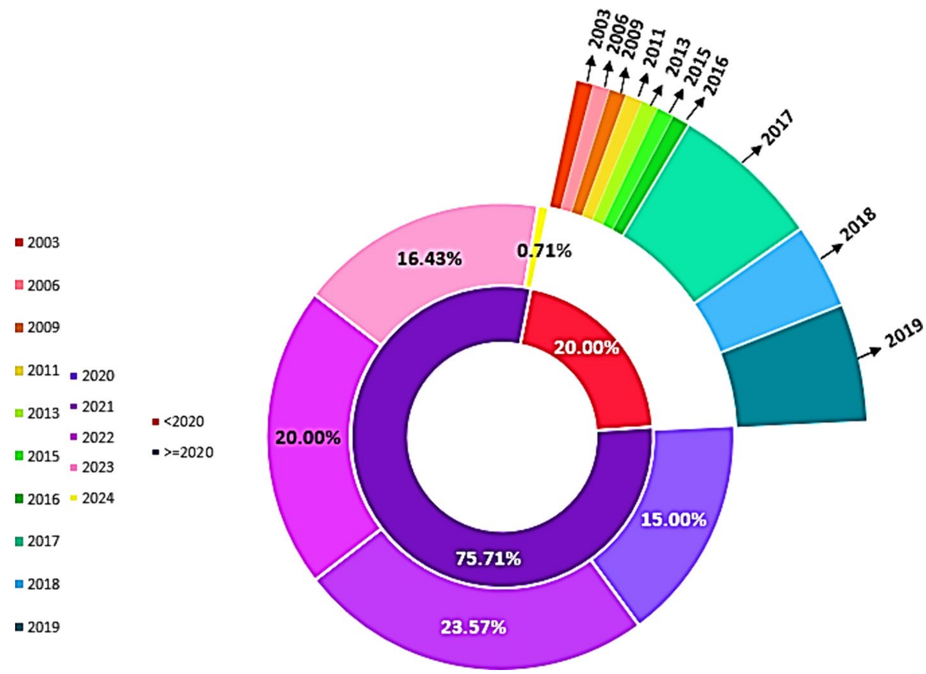
Fig. 1 Mix proportions of SCC and conventional concrete

alone, owing to rapid urbanization will lead to extensive CO_2 emissions over the next two decades and Chennai will emit 230 million tonnes of CO_2 by 2040. Due to rapid population growth, industrial development is vigorous, generating a large amount of trash pollution-causing particles, and harmful when dumping them into landfills. Switching to renewable energy sources for building operating needs would be an imperative aspect in lowering emissions in the construction industry sector, taking a step towards a sustainable environment. Reusing wreckage from demolition for new construction and switching from regular cement to low-carbon cement are two examples of ways to cut carbon emissions locally and globally (Puja et al. 2018). As a result, several unique materials from diverse sources were integrated with special concrete to cut down the amount of cement mentioned in this paper.

The SCMs shall be pozzolanic and react by taking part in the production of C-S-H gel throughout the hydration phase. Fly ash (FA) with low and high volume (Shen et al. 2022), silica fume (SF) (Nouraldin et al. 2022), nano silica (Erhan et al. 2019), metakaolin (MK) (Abderrazak et al. 2023; Parviz and Leyla 2022), ground granulated blast furnace slag (GGBS) (Piotr 2023), rice husk ash (RHA) (Aysha and Vivek 2021; Sobuz et al. 2022) and other standard SCM were used often in SCC up to this point. When utilized in binary, ternary, and poly-blended forms, they serve to boost the mechanical, durability, and microstructure characteristics (Vivek 2021; Vivek 2022). FA was primarily used to improve the fresh characteristics and increase the strength of SCC as it aged, while SF improved the strength (Mustapha et al. 2021). These industrial spinoffs reduce cement clinker usage and create plastic shrinkage, where the study of fracture mechanics originates in SCC. Cracking is very common in concrete as it is the most common distress and causes catastrophic failure (Bouali et al. 2022). In 1910 the idea of introducing fibers inside the concrete was made by Portar to enhance its strength. The initial use of fibers was animal hairs for reinforcement in masonry mortars and straws in huts with clay material (Mitra et al. 2020). At a hardened state, the concrete shows micro-cracks formation which makes them weak by forming a plane to failure, which was improved by the addition of metallic, non-metallic, natural, and synthetic fibers Viz. steel fibers, glass fibers, polypropylene fibers (PP), abaca fibers (AF), activated jute fiber (AJF). Fibers were embedded, which increased strength while also bridging fractures, delaying the propagation of cracks, enhancing the post-cracking response of a flexural specimen, and reducing the creep effect brought on by the high paste content in SCC (Vivek and Prabalini 2021; Prabu et al. 2020).

The publications period of the articles in SCC was used between 2003 and 2023 in a holistic approach as shown in Fig. 2. However, SCC's potential research works were

Fig. 2 Year of publications



refined for the last four years ranged between 2020 and 2023. This stipulated systematic review of literature, discusses the impact of innovative SCMs and fibers on SCC behaviour as specified in Fig. 2. The highlighting keywords used were SCC, SCMs, and fibers on fresh, mechanical, durability, and microstructure properties. Most of the articles reviewed were experimental investigations of SCC and few analytical studies were examined.

From the available works of literature, the utilization of different percentages of SCMs as cement and fine aggregate replacement along with fiber additions to arrive at optimum mixes were presented and examined for fresh, mechanical, durability, and microstructure properties. Very less works of literature were considered for numerical and analytical frameworks. Based on the findings from the review of literature, it has been assessed for future scope by developing tailor-made SCMs for producing greener SCC with natural fiber additions for sustainability in terms of products and society.

2 Methodology

This section discusses the procedures used to carry out a thorough evaluation of the literature. To make it clear the stages of work are reported schematically as shown in Fig. 3. To start with the basic queries on the research include an analysis - how to address the research topic and

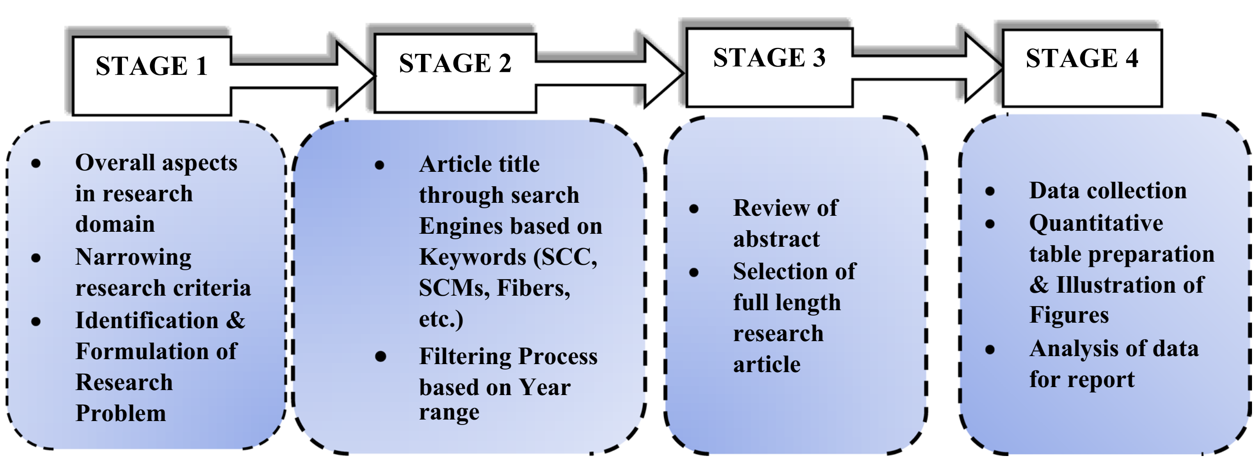


Fig. 3 Methodology in stages

why researchers add SCM and fibers in SCC; comparison of findings & extrapolation made; identified the gaps in the existing research & proposed future opportunities through research and innovations. The research articles were collected from the online sources of the "Science Direct" web site based on the website SCMs and Fibers based SCC: fresh, mechanical, durability properties, microstructure studies, fracture characteristics, etc. were filtered out separately in the above properties mentioned.

The forty-seven key characteristics were investigated experimentally by numerous authors to determine the resultant impact of SCMs and fibers on SCC. Further, these primary properties were classified into 6 categories qualitatively and are synoptically depicted in Fig. 4. The quantitative evaluation of the outcomes is illustrated in Fig. 5, which enables us to identify the properties that were frequently researched and aid in pinpointing literature gaps.

3 Material Characteristics in SCC

3.1 Modern SCMs & Fibers Used- Properties

SCMs are finely powdered material that combines with cement, resulting in the hardened strength by the pozzolanic effect, hydraulic effect, or both. According to past research findings, some of the frequently used SCMs were combined with recent materials to create sustainable concrete as FA with finely powdered glass cullet (FPGC) (Mugahed et al. 2022), graphene oxide(GO) in fly ash (FA) SCC (Veerendrakumar et al. 2022; Manikanta et al. 2021), industrial waste products like copper slag (CS) (Rahul and Rizwan 2020), zeolite powder (Sai et al. 2021), waste marble slurry (WMS) with SF (Rakesh et al. 2021), MK and limestone filler (LF) (Gemma et al. 2022), brick and glass powder (Bouleghebar et al. 2023), construction and demolition waste (Imane et al. 2022), metallurgical by-product ground ferronickel slag (GFNS) (Nuruzzaman et al. 2023), limestone powder (Daoud and Mahgoub 2021), calcined clay (CC) (Boakye

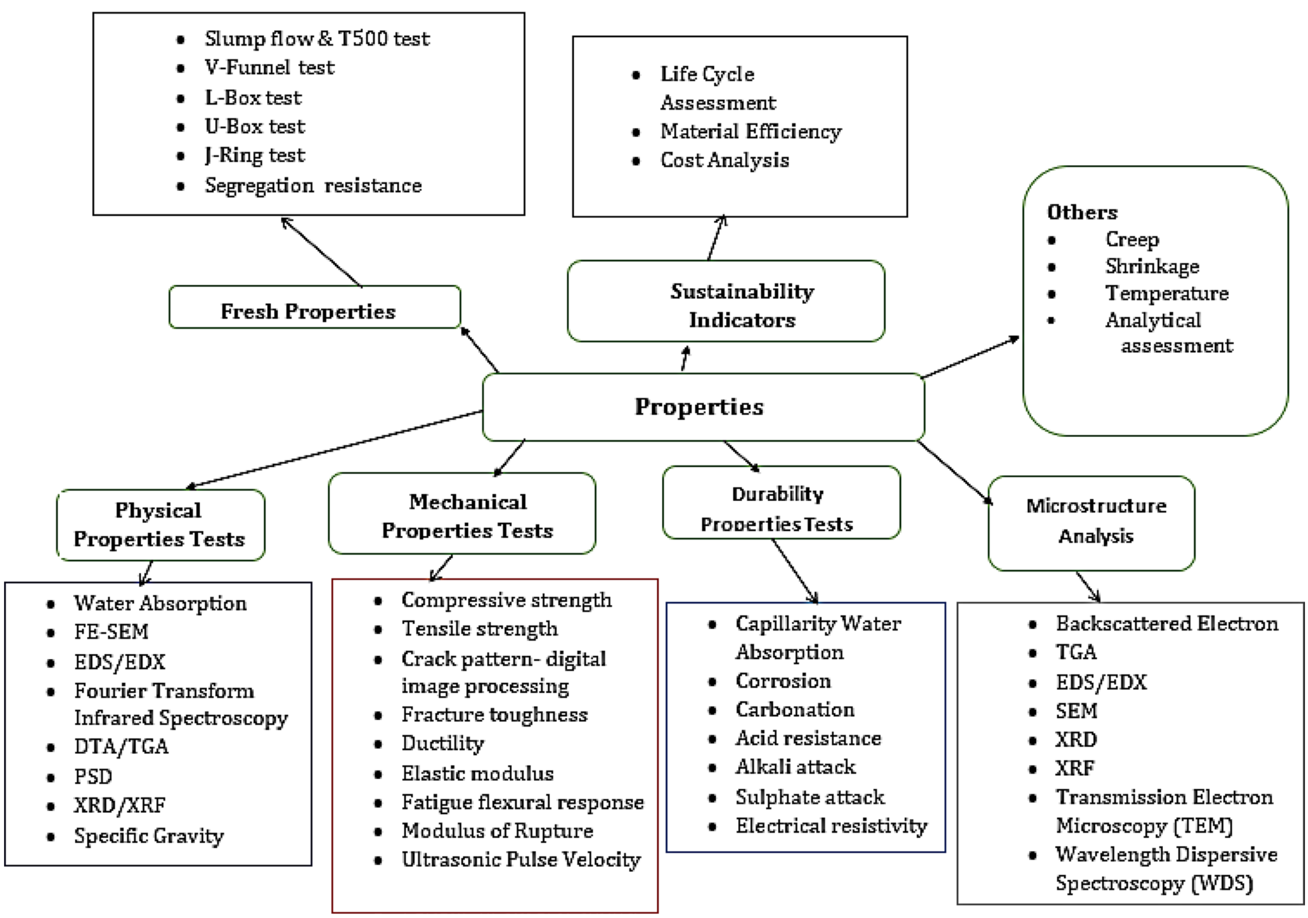


Fig. 4 List of properties collected from different Author's research findings

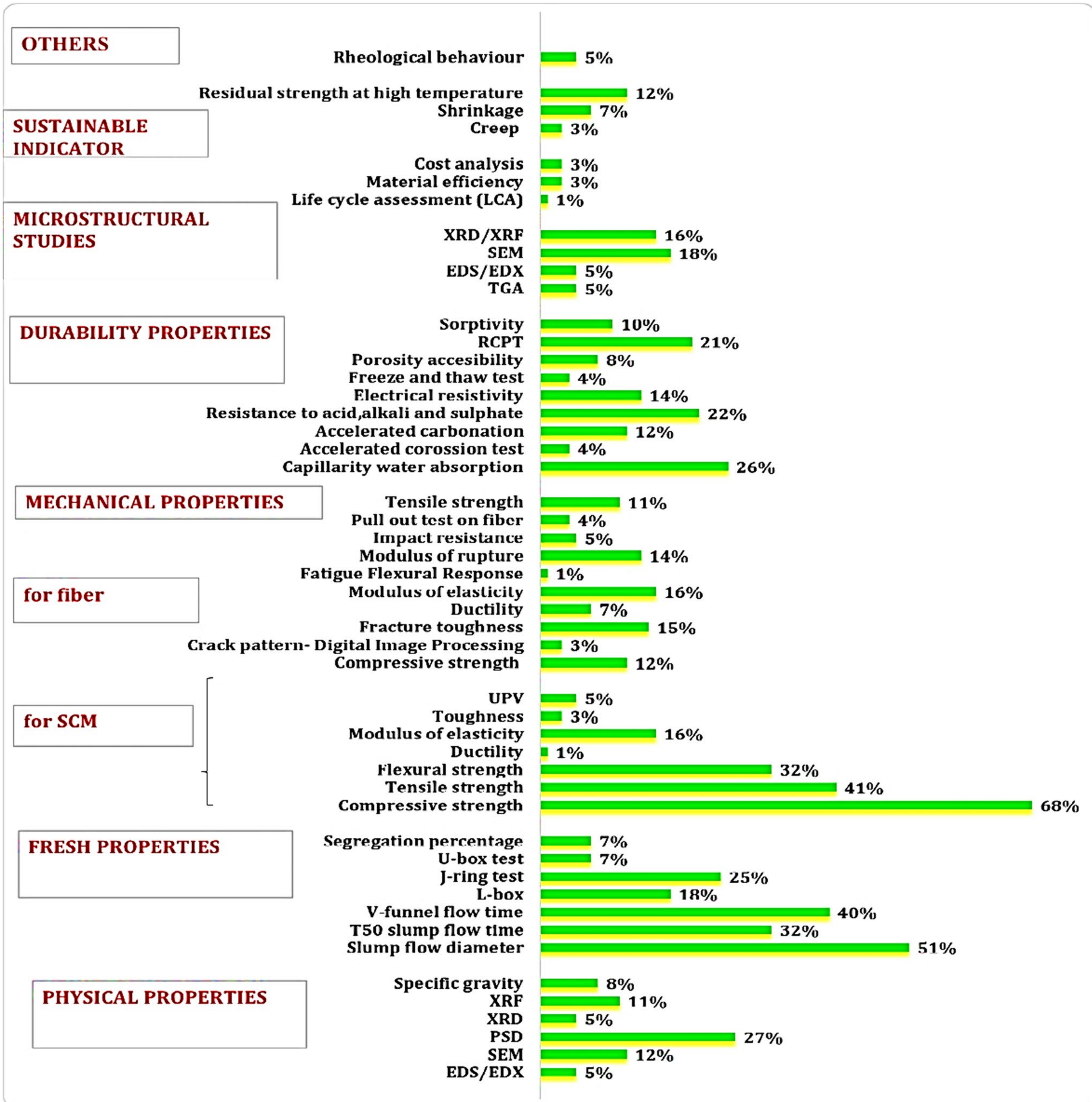


Fig. 5 Type of properties studied by different Authors in percentage

and Khorami 2023),bio-composite waste like egg shell (Nahla et al. 2021), nano agricultural waste (Bassam et al. 2023). More emphasis was placed on industrial by-products like alccofine, an ultrafine slag which is divided into three forms alccofine (Al)-1101 (rich in calcium silicate), alccofine (Al)-1203, and alccofine (Al)-1206 (poor calcium silicate) mostly used to replace SF (Bhanavath and Sivakumar 2021); likewise, steel slag powder (SSP) along with MK (Zhihong et al. 2019), granite powder (GP) and waste from incineration processes like biomass ash (BMA) used in quaternary blended high-strength SCC (Gemma et al. 2020). Other than industrial by-products, natural by-products are given greater attention these days like volcanic pumice powder (VPP) (Gamil et al. 2022), sandstone waste (Prarthita et al. 2021), recycled concrete powder (RCP) in SCC mortars (Veera 2021), hollow glass microsphere (HGM) (Sergio et al. 2022), marble and granite waste (MGW) (Mara et al. 2022) however to lower the cement concentration, they were blended in a variety of ways, from binary to poly blends. In the binary blend, the cement content is reduced to 440 kg/m^3

whereas in the ternary blend, it is reduced from 620 to 372 kg/m3 (Chopra et al. 2015; Leung et al. 2016). Table 1 lists the elemental composition of these novel SCMs.

According to the survey made from literature, poly blend concrete received less attention than binary, ternary, and quaternary blends (Fig. 6). Furthermore, there were fewer studies on the inclusion of fibers alone in SCC than replacing cement with SCM alone as the fibers addition entangle and reduces the flowability, which is one of the important properties of SCC. Due to the spectacular improvement in characteristics required for SCC, researchers are now focusing more on the inclusion of both fibers and SCM (Fig. 7). Most research works were based on the inclusion of steel fiber but later non-metallic fibers like GF, cellulose, asbestos, PP, carbon fiber were used but considering eco-friendly SCC natural fiber like sisal fiber, Lechugilla fiber, ladies finger fiber, Inula viscosa Fibers, jute fiber, roselle fiber, abaca fiber, kenaf fiber, and basalt fiber were investigated (Adil et al. 2022; Rahesh and Mini 2019; Dávila-Pompermayer et al. 2020). Different varieties of ST were employed to enhance the flexural strength including hook-end fiber, linear fiber, flat-end type, synthetic fiber such as nylon, aramid, alkali-resistant type glass fiber an PVA (Ahmad et al. 2022). Recent research has used fibers like shape memory alloy (SMA) (Aslani et al. 2020), Waste Galvanized Copper Wire Fiber (Sobuz et al. 2022), and recycled plastic fiber (Chunru et al. 2022). In general, fibers are added to the concrete to give good tensile strength to combat its weakness and prevent catastrophic breakdown. Among fibers of metallic/non-metallic/synthetic/natural fibers, each has unique properties that are mentioned in Table 2 although the inferred tensile characteristics improve based on different aspect ratios.

The principal characteristics of SCMs and fibers intended for use in SCC are as follows:

Incorporation of SCMs leads to an increase in powder content would result in fresh empirical properties tests as per EFNARC guidelines (EFNARC 2002, 2005), the use of SCMs in binary and ternary blended forms improved mechanical properties compared to control mix (Karthik et al. 2021; Vivek and Dhinakaran 2017b), and the addition fibers reduced workability whereas tensile and flexure properties were improved (Sutapa et al. 2020).

4 SCC Mix Design

While designing the SCC mix, the key factors considered were the powder content, coarse aggregate (CA), water-to-powder/binder ratio, superplasticizer (SP), and viscosity-modifying admixture (VMA) dosages. When compared to normal concrete (NC) the primary component in SCC mixes to achieve the flow is the fines or powder content of size

Table 1 Basic properties of SCMs

Component (%)	FPGC (Mugahed et al. 2022)	GFNS (Nuruzzaman et al. 2023)	WMS (Rakesh et al. 2021)	CC (Boakye and Khorami 2023)	Al (Bode et al. 2020)	SSP (Zhihong et al. 2019)	GP (Gemma et al. 2020)	BMA (Gemma et al. 2020)	VPP (Gamil et al. 2022)	SSW (Prarthita et al. 2021)	HGM (Sergio et al. 2022)	MGW (Mara et al. 2022)
SiO_2	69.14	51.42	5.98	62.77	37.53	26.28	70.4	40	46.5	81.05	79.26	69.55
Al_2O_3	13.86	2.88	0.98	18.71	24.57	11.38	15.2	16.6	17.59	8.225	0.14	16.24
Fe_2O_3	0.24	12.85	0.82	11.68	0.92	5.24	2	5.5	7.33	0.39	0.02	2.55
CaO	3.16	0.48	46.09	0.25	29.46	48	1	10.2	12.52	0.285	14.7	–
MgO	0.68	30.58	7.06	1.89	5.23	4.86	0.35	2.8	6.94	0.525	0.28	0.7
SO_3	4.08	0.05	–	0.19	0.18	0.98	–	2.4	0.42	0.06	0.3	0.19
K_2O	0.01	0.03	0.26	2.12	0.61	0.13	5.5	6.9	1.17	5.595	–	5.56
Na_2O	0.01	0.08	–	0.03	0.032	–	3.7	1.6	2.58	0.2	4.78	–
Ignition loss	0.16	–	38.33	1.46	0.58	–	1	2.7	1.61	–	–	0.75
Specific gravity (kg/cm^3)	1.02	2.95	–	–	–	–	2.56	2.68	2.61	2.62	–	–
Specific surface area (m^2/g)	206	–	–	–	–	–	8.77	0.63	–	–	–	–

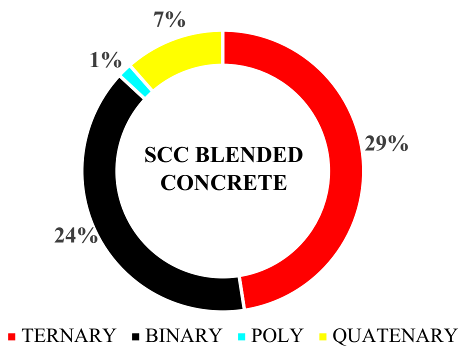


Fig. 6 Study statistics on SCC blended concrete

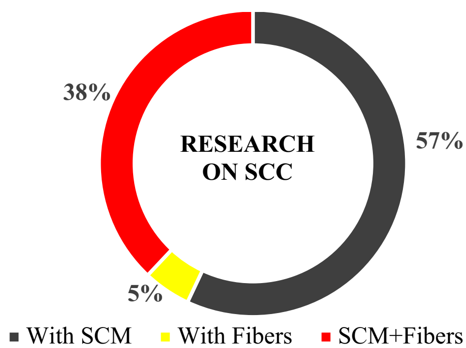


Fig. 7 SCC with and without fiber proportions

smaller than 0.125 mm. Its dosage depends on the flowability nature of SCC. To achieve good stability of the mixture at constant fluidity and to avoid segregation VMA is added. The workability property of prepared SCC mixes may be defined by their equilibrium, which must be preserved for a predetermined amount of time to facilitate the transport of the mix from the batching/production location to the site from placement to the finishing process. There was no standard design method for SCC in earlier periods, so many companies/institutions such as ready mixed, precast companies, etc. adopted their mix-design methods. They were classified as an empirical method, rheology-based method, particle packing method, and statistical method.

With the use of SP dosages, Okamura and Ouchi modified the mix design of SCC by lowering the CA and increasing the cement percentage for enhanced flowability (Tawfeeq and Ganesh 2022). The binder paste is the vehicle to transport near the aggregate, the paste volume should be greater than the void volume so that the aggregates can be fully coated with the paste and reduce the aggregate friction. Domone (2006) stated the range of cement content used by 95% of the researchers was more than 400 kg/m^3 and high strength SCC was about 600 kg/m^3. Hence the powder content increased by adding SCMs, thus the cement content could be reduced as formulated in SCC mix design (Lang et al. 2022). Nowadays in most of the research works, the SCC mix was finalized by meeting the European Federation of National Associations Representation for Concrete EFNARC (2002), which later affirmed EFNARC (2005) guidelines. In the Indian scenario, IS 10262:2019 (IS 10262 2019) describes the process for the mix design.

The crucial aspect of the SCC mix design was the choice of selection and gradation of aggregates. Since the coarse aggregate size of not less than 12.5 mm is required for ease of SCC flow characteristics. The particle size of less than 0.25 mm as powder content (SCMs) is mostly used as fine aggregate as well as cement also significant parameters influencing SCC rheological behaviour. In SCC of high strength/high performance of special type has cement as the major constituents will be catered by substituting SCMs as replacers for cement. The issues of blockage, segregation, and bleeding are major drawbacks in SCC but could be overcome by the proper formulation of mix design with appropriate SCM percentages, superplasticizer, and viscosity

Table 2 Properties of different types of fibers

Type of fiber [REF.]	Tensile strength (MPa)	Density (g/cm^3)	Modulus of elasticity (GPa)
GF (Adil et al. 2022)	3400	2.6	77
SFF (Aliha et al. 2018)	570–660	0.91	4.7
Sisal (Rahesh and Mini 2019)	600–700	1.3–1.5	09–22
Nylon (Rahesh and Mini 2019)	750–1000	1.14	2.5–5.17
BCSF (Ali et al. 2021)	2000	–	190
ST (Gamil et al. 2022)	2500	7.8	200
PP (Liu et al. 2019)	680	0.91	5
AF (Vivek et al. 2023)	650–750	–	–
Roselle (Prakash et al. 2021)	150–400	1.35	2.76
BF (Adil et al. 2022)	4000–4500	2.8	88
CF (Debalina et al. 2021)	290	1.81	–

Table 3 Test methods for the SCC characteristics (EFNARC 2002, 2005)

SCC characteristics	Test methods
Flowability	Slump-flow test
Viscosity	T_{500} slump flow test/V-funnel test/Orimet
Passing ability	L-box test, U-box, J-ring
Segregation	Segregation resistance (sieve) test

Table 4 Range of acceptance according to EFNARC guidelines (EFNARC 2002, 2005)

Empirical tests	Unit	Range	
		Min.	Max.
Slump flow	mm	650	800
T_{500} slump flow	Sec	2	5
J-ring	mm	0	10
V-funnel	Sec	6	12
V-funnel at T 5 minutes	Sec	0	3
L-box	(h2/h1)	0.8	1.0
U-box	(h2-h1)	0	30
GTM Screen stability test	%	0	15
Orimet	Sec	3	15

modifying agent dosages by repeated test trials in the laboratory to satisfy EFNARC guidelines. The fiber additions cause a balling effect and curtail the SCC flowability risking more blockages. This failure could be overcome by treating the fibers chemically with SCMs to prevent the surface friction exhibited between powder content and aggregate and by using computational fluid dynamics simulations for the orientation of fibers. Further, optimal superplasticizer and VMA dosages ensure the conglomeration and homogeneity of the SCC mix. Hence, the combination of SCMs and fibers in SCC mix design is a challenging task that reflects scientifically in all respects.

5 Influence of SCMS and Fibers in SCC

5.1 Effect on Fresh Properties

In SCC fresh properties, significant parameters were the initiation and resistance to flow. This would be achieved by conducting fresh properties of SCC that could satisfy its unique characteristics with EFNARC guidelines (EFNARC 2002, 2005). Tables 3, 4 comprise a list of techniques and the range of each. Nowadays, rock crushing reserves are employed as a fine aggregate due to the depletion of river sand, however, it is unknown how this may affect the flow and strength nature of SCC (Suriya et al. 2023). Prakash and Manu (2011) replaced 100% of river sand with M-sand and found that the presence of fineness demands more water but the growth of SCC was favourable due to high paste volume. Yamuna et al. (2023) compared M-sand and river sand in SCC and concluded that due to low silt content in M-sand, its proper gradation and its specific gravity are higher than river sand thus improving the fresh, mechanical, and durability properties. Fresh characteristics were primarily impacted by the water-to-binder ratio (w/b) (Gemma et al. 2020).

SCMs could improve the pore spaces in the concrete. If the specific surface area was larger in SCMs then it would absorb more water and could reduce the free water thus affecting the fluidity nature and leading to the introduction of superplasticizers (Bassam et al. 2023). Mostly third-generation superplasticizers Viz. Polycarboxylates, Polyacrylates, and Monovinyl alcohols were used in practice because of the bulky side chain that creates steric hindrance which improves the dispersion and lasts longer (Lang et al. 2022). It is found that FA enhances the workability by about 70% due to the “ball bearing effect” (Ranbir and Singh 2021), a similar idea was shared by Mugahed et al. (2022) that FPGC reduces slump flow by 15.9% due to high intermolecular friction between the particles but the addition of FA up to 50% compensated the workability issues. The flow behaviour was not only influenced by FA dosage but also predominantly by the w/c ratio. Sergio et al. (2022) found akin characteristics to FA by replacing cement with HGM at 5% by weight and has shown high workability because of the ball bearing effect.

Choudhary et al. (2020) found that FA was spherical and had improved fluidity whereas SF was rougher thus reducing fluidity. Bouleghebar et al. (2023) stated that the glass powder as SCM enhances the flowability with a superplasticizer (SP)as compared with brick waste at the same time the strength improvement for glass powder (16%) was superior over the brick powder (8%). The cost-effective sustainable concrete limestone powder of second grade can be used as the replacement for cement in SCC up to 20% without compromising the flow nature but increasing the amount leads to stickiness which makes the concrete viscous (Daoud and Mahgoub 2021).

Hence any SCMs up to the optimum level enhance the fluidity because of the large surface area as shown in Table 1. Similarly, Chidambaram et al. (2022) employed alccofine in place of a portion of the cement to boost workability by 30%; beyond that, workability was impacted by hydration undulation. Thus, the solid volume fraction increased the rheological parameters and altered the flowability nature. Rheological properties are described more specifically and quantitatively than workability properties. The yield stress and viscidity were higher in the ternary mix than in the binary mix (Karthik et al. 2021). To develop an eco-friendly type of SCC, Prarthita et al. (2021) incorporated sandstone waste (SSW) and observed a 760 mm slump flow of up to 30% partial cement replacement. It enhanced strength because of its pozzolanic nature. Waste like MGW contributed more to flowability rather than strength (Mara et al. 2022). SCM with pozzolanic nature set within a short period so Imane et al. (2022) introduced construction and demolition waste as SCM in SCC and found that it retards the setting nature but starts to set after 60min. Apart from SCM and fibers, poor passing ability and blockage may occur due to the size of the aggregate used. Around 70% of research works used an aggregate of size 16 and 20 mm but in FR-SCC, 10–12.5mm was feasible for good compatibility. Cenk at al. (2018) assessed the blocking risk and segregation resistance of aggregate in a fresh state for assessing the flowability accurately in SCC through stimulation by numerical modeling-computational fluid dynamics (CFD). This allows for the investigation of actual and complex case blockage risk. To acquire a deeper understanding of the rheological behaviour of paste Raoudha et al. (2023) employed numerical stimulation CFD through L-box test. The use of CFD techniques lessens the need for SCC to test the status of workability by trial and error and helps to precisely characterize behaviour.

By incorporating many kinds of natural, synthetic, and mineral fibers, SCC progressed. According to the survey, natural fibers in the SCC property study were less than metallic fibers (Fig. 8). This is primarily because metallic fibers have a higher tensile strength than natural fibers. As may be seen in Fig. 9, hybrid fiber combinations underwent less research than mono fiber. The incorporation of fibers resulted in reduced flow but improved strength, ductility, and durability behaviour under static load. Incorporating SCM like alccofine, and VPP with steel fibers(ST) provided good flowability and fulfilled the EFNARC conditions (EFNARC 2002, 2005). From the study, it was concluded that ST had restricted the rate of segregation and bleeding. The restriction to segregation was more for hooked end fibers when compared with other types because it restricted the coarse aggregate (CA) to settle downwards while flowing, whereas the microfibers reduced the bleeding action because of the larger surface area which has limited water to move upwards. The hooked end ST has not only restricted the segregation but glass fiber (GF) also has a high binding nature avoiding immediate coarse aggregate (CA) settlement (Vivek et al. 2022). In the case of hybrid fiber addition, to compensate for the flowability issue SCMs like FA, and SF were added (Ali et al. 2021; Ramkumar and Kannan Rajkumar 2022). The addition of a low aspect ratio (macro fibers) compared with microfibers proved to show better workability properties (Kazim et al. 2021; Duy et al. 2022). Many studies were done by embedding ST as it enhanced the strength but it had demerits of corrosion occurrence.

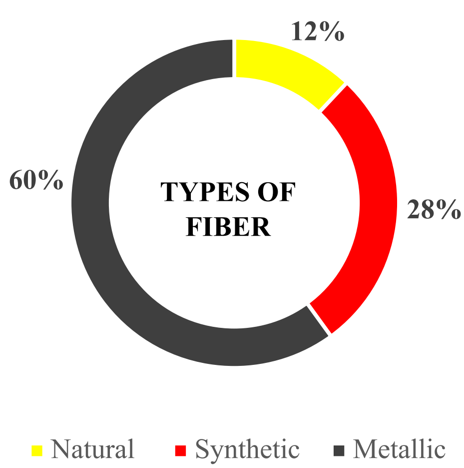


Fig. 8 Proportion of fibers studied

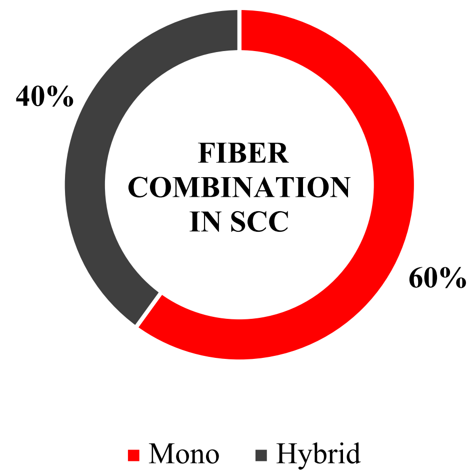


Fig. 9 Fiber combination proportion

To overcome the effect of corrosion, Rizwan and Behrouz (2022) replaced the ST with five synthetic fibers like nylon, alkali-resistant glass, polypropylene (PP) (Sadrmomtazi et al. 2020; Liu et al. 2019), carbon (CF), and polyvinyl alcohol fibers(PVA), synthetic fiber demanded more HRWR admixture for 200 mm flow. In FR-SCC, ST does not affect yield stress and could result in good workability whereas the addition of GF, carbon fiber (CF), and PP has increased the yield stress and obstructed the workability. Those ill effects could be overcome by adding GGBS (Debalina et al. 2021). Rakibul et al. (2023) made jute fiber-reinforced SCC as it has an uneven surface so the bond can be strengthened. Up to 0.75% workability performance was at a satisfactory level but at more than 0.5% the stability starts to increase. Prakash et al. (2021) incorporated natural fiber called roselle fiber up to 4% by the binder weight with FA and MK. The EFNARC conditions were satisfied with a 3% addition of Roselle fiber in fresh properties beyond that it doesn't satisfy.

Abaca fiber (AF) and polypropylene fiber were introduced by Vivek et al. (2023) in mono and hybrid forms with SCM like SF, FA, GGBS, and Al. Beyond a 1.5% fiber addition, the flow and passing capabilities are severely restricted because natural fiber requires more water than PF while Al keeps SCC functional. This is mainly because of the hydrophilic nature of natural fibers, therefore they can absorb more water in concrete and thus can be optimized by giving different treatments to make them hydrophobic and rougher which boosts their adhesion between concrete and fiber (Yashas et al. 2019). Nafissa et al. (2021) compared the permanganate treatment to the alkali treatment by immersing pre-treated alkaline fibers in a 3% potassium permanganate solution and the inula viscosa fiber in a 3% sodium hydroxide solution. They found that the permanganate treatment was effective at both concerting fibers to hydrophobicity and mechanical strength.

Isiaka et al. (2020) treated natural fibers like banana fiber, Dombeya Buettneri, and Combretum Racemosum in a solution of acetyl anhydride of 4% (optimum) for 3 hours before being washed with tap water to eliminate acids. It enhances dimensional stability and resistance to environmental deterioration by removing hydrogen atoms from the hydrophilic hydroxyl branches of cellulose molecules, which decreases the susceptibility of fibers to moisture absorption. Thus, it can be concluded that natural fibers can be utilized successfully in environmentally friendly SCC by being treated to improve the qualities even further. By EFNARC requirements, Table 5 shows the findings of the effect of slump flow spread diameter and mechanical properties by the use of SCMs in binary, ternary, and quaternary forms.

Figure 10 shows the slump flow spread diameter obtained for different SCMs. According to EFNARC 2005 (EFNARC 2002), the slump flow classes were classified as SF1 for the slump flow range between 550 to 650 mm, SF2 for the slump flow range between 660 to 750 mm, and SF3 for the slump flow range between 760 to 850 mm. The results reported by several authors have shown that most results fell under the slump flow class SF1, then followed by the SF2 range, and less SCMs fell under the SF3 range. The reason was due to the highest water demand requirements for the flow properties and also depends on the surface area of SCMs used. Further, the optimum dosages of water to binder ratio, superplasticizers, and VMA dosages also had a significant role in arriving flow characteristics in SCC. Hence, the reported results of slump flow by different SCMs in SCC have satisfied the limits laid by EFNARC guidelines.

Table 6 shows the outcomes of adding fibers to SCC, which had an impact on slump flow spread diameter and, in most cases, produced a range of values that were acceptable by EFNARC standards. It was also deduced that the flow had been impacted by adding fibers.

Figure 11 illustrates the slump flow values of SCC using the addition of fibers. The addition of fibers resulted in the reduction of flow behaviour in SCC. This was due to the surface area, and hydrophobic and hydrophilic nature of fibers used. Most of the reported results fell under SF1 of slump flow class and ranged between 550 and 650 mm. Then the rest is followed by the SF2 range category. To overcome these drawbacks, the surface of fibers would be coated with the blending of SCMs ahead of the casting schedule to curtail the surface friction exhibited at the fresh state properties of SCC.

5.2 Effect on Mechanical Properties

The w/c ratio was the primary factor that affected the mechanical characteristics (Gemma et al. 2020). Due to dropped pozzolanic reaction and greater shrinkage effect, the use of the most widespread SCM this FA improved the delayed strength of the concrete (Adil et al. 2022; Bode et al. 2020). Similar to this, Nuruzzaman et al. (2023) recently used GFNS, which initially gives low heat of hydration as the replacement percentage grows due to low calcium content, causing the ITZ to thicken from 55 to 73 µm for 35% to 50% replacement of cement nevertheless the fluidity maintained since the early stage produces fewer reactive products. Veerendrakumar et al. (2022) compensated for the negative impact of fly ash (FA) which is delayed early strength with the incorporation of graphene oxide (GO). Karthik et al. (2021) stated that the addition of SF and FA in ternary form showed greater mechanical and durability characteristics but showed a negative impact on fresh behaviour so FA was mostly added to improve the fresh properties whereas SF was added to improve the mechanical properties. Thiago et al. (2022) tested SCC with high levels of mineral admixture replacing 60% of cement with MK, RHA, LF, and hydrated lime. The high-level addition reduced the compressive strength but could achieve about 22 MPa and 46 MPa tested in 28 days. In blended concrete, binary mix reduced the strength by about 20% whereas ternary mix strength was reduced by 15% but the resistivity increased by doubled (Manikanta et al. 2021). The efficiency of MK was higher than that of other SCMs because, when SF and MK were compared in terms of their pozzolanic natures, MK interacted with CH to produce calcium hydro alumina silicate beside calcium hydro aluminate, whereas SF combined with CH to generate CSH gel (Thiago et al. 2022). Mohamed et al. (2023) substituted 40% of the cement with a quaternary blend of 15% SF, 5% MK, and 20% limestone powder, which had compressive strengths that exceeded

Table 5 Slump flow and mechanical properties of SCMs without fibers

Ref.	SCMs	Slump flow spread Dia. (mm)	Optimum (%)	Compressive strength at 28 days	Tensile strength	Flexural strength
Mustaphaet al. (2021), Karthik etal. (2021)	FA-20%, SF-10%	700	FA-20%, SF-10%	44.82	4.52	40.1
Manikanta et al. (2021)	FA-20% GO-2%	600	FA-20% GO-2%	60	–	–
	FA-20%, SF-10%, GO-6%	550	FA-20%, SF-10%, GO-6%	55	–	–
Rakesh et al. (2021)	10% WMS, 15%FA, 5% SF	–	10% WMS, 15%FA, 5% SF	62.56	–	–
Gemma et al. (2022)	lime stone filler (LF), MK	–	–	38.26	–	–
	lime stone filler (LF), MK	–	–	42.89	–	–
Zhihong et al. (2019)	SSP-10%, FA-20%	680	SSP-10%, FA-20%	50	3.25	–
Prarthita et al. (2021)	SS-15%	800	SS-15%	32.9	–	4.678
Veera (2021)	RCP-20%	–	RCP-20%	77.1	–	–
Sergio et al. (2022)	HGM-5%	643.5	HGM-5%	45.9	2.86	4.11
Mara et al. (2022)	MK, LF, MGW	680	–	44	4.7	–
	MK, LF, MGW	670	–	43.3	4.5	–
Bode et al. (2020)	FA-25%, Al-10%	550–612	FA-25%, Al-10%	34.23	3.42	5.12
Thiago et al. (2022)	MK30-LF30	760	MK30-LF30	37	–	–
	MK20-RHA30-LF10	740	MK20-RHA30-LF10	45	–	–
Prithiviraj and Saravanan (2020, 2022)	Al-30%	600	Al-30%	48.13	–	4.46

125 MPa and at all temperatures conditions and 20% limestone powder enhances both fresh and mechanical properties of ultra-high-performance SCC. When MK was added to FR-SCC, it showed the highest deflection resistance and fracture energy, but the overall elastic modulus was the same for both MK and SF (Burcu and Mehmet 2018). The practical method for obtaining high fresh, toughened, and durable qualities was to utilize 25% FA and 10% alccofine (Al) during all curing periods (Bode et al. 2020). Al with GGBS performed well for high-strength SCC (M60-M100) (Ranjitha et al. 2021). Apart from common SCM usage, waste products like FPGC, and RCP were used in optimum quantities to enhance the strength without any negative effect (Mugahed et al. 2022; Veera 2021). Pozzolanic materials like CC enhance the compressive strength and flexural strength up to 10% beyond that it acts as a filler and reduces the mechanical strength (Boakye and Khorami 2023). Eggshell ashes from bio-waste increase later compressive strength but decrease mechanical strength due to its addition; nonetheless, waste plastic fiber (1%) enhances mechanical characteristics (Nahla et al. 2021). Chunru et al. (2022) employed recycled plastic waste, which interfered with the flow nature but increased the compressive strength due to its internal confinement. When combined with SCMs, it further raised the strength by 18.28% due to its good coupling effect. Recycled aggregates were used up to 100% in SCC without compensating on its properties with the help of SF, FA (Ranbir and Singh 2021). To improve the deformation capacity of beams, fracture toughness, and post-peak behaviour, fibers were introduced (Gamil et al. 2022; Ahmad et al. 2022). Each fiber addition has provided different outcomes because the performance enhancement depends on aspect ratio, distribution, volume fraction, and tensile load capacity as shown in Table 5. When compared to other types of fiber, the inclusion of ST generally increased compressive strength because the hook end exhibited peak compressive strength and pull-out behaviour when the fiber was shorter. Comparing the straight fiber of different lengths, the longest fiber showed high compressive strength because the shortest fiber doesn't give a proper homogenized mix. The volume fraction like 1.2% macro and 0.3% micro-ST showed the highest mechanical properties because of the large proportion in macro-ST. Microfiber of 1% volume fraction led to more compressive strength. In terms of good ductility, post crack phenomenon under high deflection; synthetic fibers were superior over ST (Rizwan and Behrouz 2022). PP fiber even though provides good tensile, impact, and flexural strength, mainly avoids brittleness and resists spalling effects due to fire (Danar et al. 2020; Farhad et al. 2019). Aslani et al. (2020) compared the flexural capacity of SMA with PP and Steel fiber, the flexural strength and

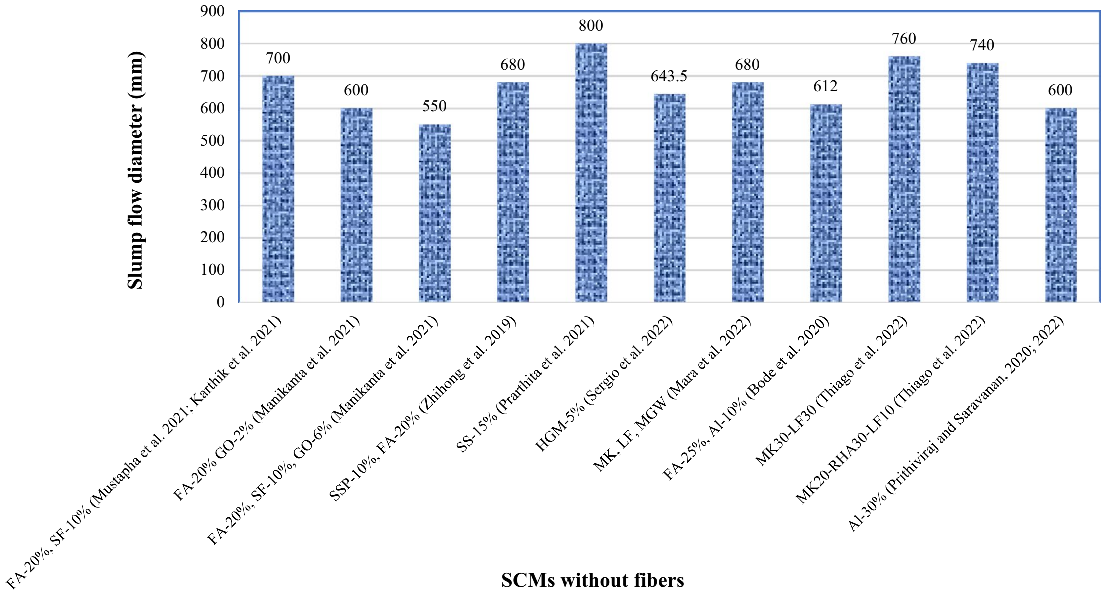


Fig. 10 Fresh properties- slump flow diameter for SCMs without fibers

deflection of SMA concrete is 3, 2 times of PP and 2, 4 times of steel fiber addition. It influences more on postponing the initial crack formation thus enhancing fracture toughness. Some fibers like discarded copper fiber even though the less flow nature of concrete but still its compression, split tensile, and flexural strength development remain below the control mix (Sobuz et al. 2022). Lakman Prabu and Vivek (2020) investigated the ternary blended SCC beams in both analytical and experimental methods. Vivek et al. (2022) combined PP and glass fibers with natural fibers like abaca fibers in hybridized forms. By stopping fractures in the prism's soffit, the mixture of PP and abaca fibers has demonstrated stronger and more ductile qualities than the glass fiber. Like abaca, roselle fibers enhanced the mechanical properties, mainly the impact loads up to 27% at 3% incorporation (Vivek et al. 2023). Mustafa (2022) incorporated natural fiber-red pine needles after refining the organic material using an alkaline treatment. When fibers of 30–40mm long it enhances both compressive and flexural tensile strength but when they are at 50mm long flexural strength enhances but reduced compressive strength than the reference mix. Comparing the result, fiber hybridization improved mechanical properties when compared to mono-fiber additions, but when fiber volume was raised past the point of maximum benefit, compressive strength decreased as a result of unequal load transmission (Rahesh and Mini 2019), while flexural strength rose (Sutapa et al. 2020). Tables 5, 6 illustrates the way the use of several SCMs exchanging cement and fibers influences compressive, tensile, and flexural strength. Basalt fiber, a naturally occurring form of fiber produced by processing basalt rocks, was investigated by Samadae et al. (2021) at different temperatures. The 7days compressive strength was 75% of its 28-day strength despite this due to the high rigidity of basalt fiber at high temperatures, the compressive strength and beyond 300°C the basalt fiber became brittle so ultimately the flexural and split tensile strength turned down. Sisal fiber was employed by Sethuraman et al. (2020) along with FA and MK. Even though sisal fiber demands more super plasticizer (SP) and VMA but still the workability issues were still balanced by the presence of FA in the mix. The addition of sisal fiber improves compressive strength because it prevents micro-crack formation and by 16.6% enhances split tensile strength. Ruslan et al. (2022) studied the polydispersed reinforcement in SCC that differs in shape and its material manufacturing type like Chelyabinka fiber, which is made of milling rolled steel which is of trapezoidal irregular shape in strip form, another one distinguished by forming oxide layer coating which resists more corrosion effect, steel fiber of brass plated in wave profile and PF. This concept highly affects the workability but Chelyabinka fiber improves the bending property, PF improves the tensile property and metallic fibers enhance the impact strength as well.

Kazim et al. (2021) researched the aspect ratio of hybrid steel FRSCC on high-volume fiber additions had influenced the tensile and flexural strength properties. It was reported that the higher aspect ratio caused lower workability but strength properties were improved and

Table 6 Slump flow and mechanical properties of SCMs with fibers

References	Fibers	w/b	Length (mm)	Diameter (mm)	Aspect ratio	Fiber addition (%)	Optimum (%)	Slump flow spread Dia. (mm)	Compressive strength (MPa)	Tensile strength (MPa)	Flexural strength (MPa)
Prakash et al. (2021)	Roselle fiber	0.33	35	–	–	1–4	3	650	34.78	3.9	4.75
Gamil et al. (2022)	Hook-end steel fiber		60–30	–	65–55	1% volume fraction	–	520	47.6	4.06	–
	Straight steel fiber	–	21–13	–	60–65		–	480	45	4.35	–
	Steel-end steel fiber		50	–	56		–	480	44.3	3.82	–
Adil et al. (2022)	Basalt fiber (BF), glass fiber (GF)	0.29	6, 12, 24	–	–	2 and 4 kg/m^3	GF-12-2	720	60	–	9
Rahesh and Mini (2019)	Sisal (S), nylon (N)	0.34	S-25, N-18	–	–	0.1	–	740	70	9.3	7.3
	Sisal (S), nylon (N)			–	–	0.2	–	700	62.5	11.3	9.86
	Sisal (S), nylon (N)			–	–	0.3	–	660	63	13.83	12.4
Vivek et al. (2022)	Abaca fiber(AF), PP, glass fiber(GF)	0.35	AF-30, GF-12, PP-30	AF-1-3, GF-13, micron, PP-1	–	AF- 0.25, 0.5,0.75 PP-0.5, 1, 1.5,2 GF-0.5, 1, 1.5,2	GF-1% AF-0.25	563	37.29	14	16
Ali et al. (2021)	Steel fiber (SF), brass coated steel fiber (BCSF), PP	0.38	SF-30, BCSF-6, PP-12	SF-0.75, BCSF-0.25, PP-0.018	SF-43, BCSF-24	SF-2, BCSF-2, PP-0, 0.05,0.1	SF-2, PP-0.1	560	70	8.16	8.5
Kazim et al. (2021)	Macro (M), micro (m) ST	0.28	M-60, m-13	M-0.9, m-0.15	M-65, m-87	1,1.5	M-1.2 m- 0.3	700	69.7	9.35	12.04
Liu et al. (2019)	ST, PP	0.33,0.3	–	–	–	SF/PP-0.5/0, 0.5/0.5, 0.5/0.75, 0.5/1	SF-0.5, PP-1	645	57	6.5	5.5

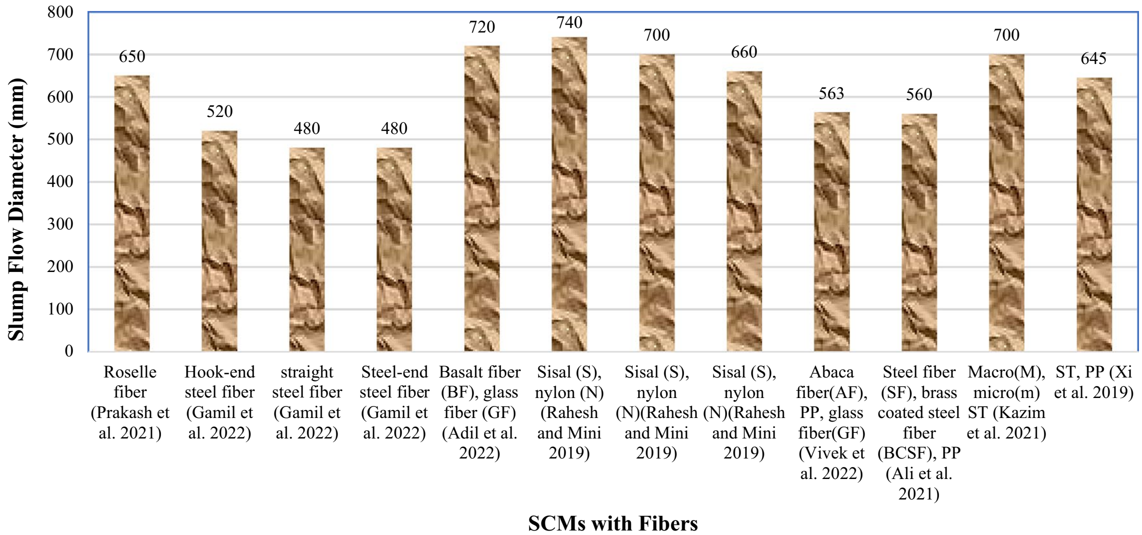


Fig. 11 Fresh properties- slump flow diameter for SCMs with fibers

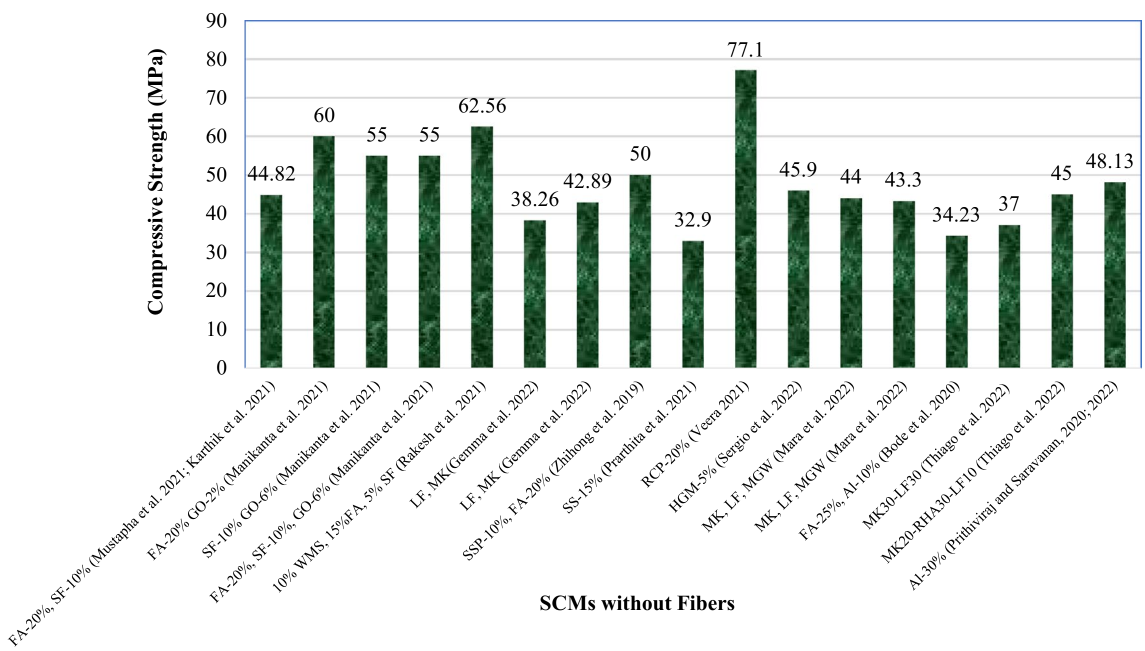


Fig. 12 Compressive strength for SCMs without fibers

vice-versa. Similar research studies were performed by other authors (Gamil et al. 2022; Yamuna et al. 2023; Duy et al. 2022; Liu et al. 2019; Akshay et al. 2021).

Even though fibers efficiently boost mechanical characteristics by bridging flaws, concrete flow, and flexural behaviour were influenced by the fiber's way of distribution towards flow (Ramiz et al. 2020). Mohammad et al. (2023b) hypothesized that fiber orientation and distribution have an important impact on enhancing mechanical strength even at minimal quantities. He used CFD for modeling the casting stages validated using slump and used the discrete element method (DEM) for stimulating fiber orientation and movement in the casting process. In this manner, the influence of fiber length and distribution with its coordinates on the mechanical and rheological properties can be adequately understood (Yun et al. 2021; Bi et al. 2020; Steffen et al. 2021).

The compressive strength results for SCMs without and with fibers reported by several authors are illustrated in Figs. 12 and 13. The highest compressive strength was obtained as 77.1 MPa (Veera 2021) without fiber additions. It was observed that the fiber additions do not have

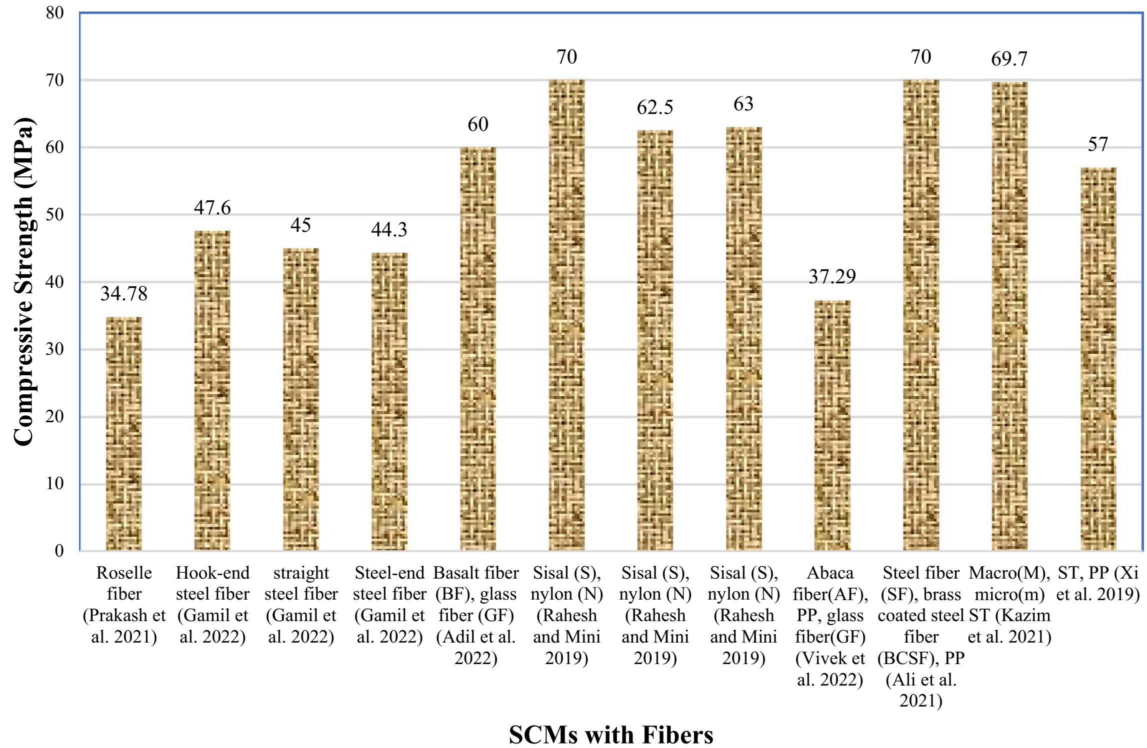


Fig. 13 Compressive strength for SCMs with fibers

a significant influence in imparting high compressive strengths. However, the addition of fibers in SCC could bridge the cracks during loading and control the propagation of cracks developed. Hence from the reported results, it is possible to produce a high-strength grade of SCC with/without fiber additions in the range between 60 – 80 MPa.

From Fig. 14, the tensile strength of SCMs has improved by the addition of fibers in the range between 4 – 14 MPa. The fibers such as sisal, nylon (Rahesh and Mini 2019), Abaca, PP, and GF (Vivek et al. 2022) in the hybrid fiber combinations resulted in the highest tensile strength characteristics. This was due to the yield strength properties of the nature, type of fibers used, and their geometric orientation.

From Fig. 15, the addition of hybrid forms of fibers AF, PP, and GF (Vivek et al. 2022) imparted the highest flexural strength was reported. A similar trend has been obtained for steel fibers in macro and micro (Kazim et al. 2021) and sisal, nylon combinations (Rahesh and Mini 2019). Hence the hybrid combinations of fibers would be more effective than mono fibers in increasing the flexural tensile strength was inferred from the results reported.

5.3 Effect on Durability Properties

Pittella et al. (2020) researched that the tightness of the mortar influenced the durability factor in the concrete. SCMs improved tightness but Karthik et al. (2021) reported that SCMs addition absorbed more water than the NSCC but MGW addition in SCC showed a reduction in water absorption by 31.34% giving positive results for flow properties (Mara et al. 2022). Because of the high packing structure, which prevents any harmful material from passing through and concurrently raises the electrical resistance, concrete with SCMs shows less weight loss under acid and base assault than concrete without SCMs. In ternary and quaternary mix, the water absorption at the same time the ingress of chloride ion got reduced so the quaternary mix was considered to be efficient. Most common minerals like FA, and SF resisted the chloride ion ingress into the concrete likewise MK whereas slag contains high C_3Aexcellently binds Cl^- ions and prevents its ingress (Thiago et al. 2022). Justification towards this Mohamed et al. (2023) replaced 40% of cement with mineral admixtures like SF, MK and inert powder like limestone powder and concluded that ternary and quaternary blends (SF-15%, MK-5%, LS-20%) showed very low sorptivity (0.008%) and absorption (0.22%). Prithiviraj and Saravanan (2020, 2022) concluded that up to 30% addition of Al improved the strength but more than that it

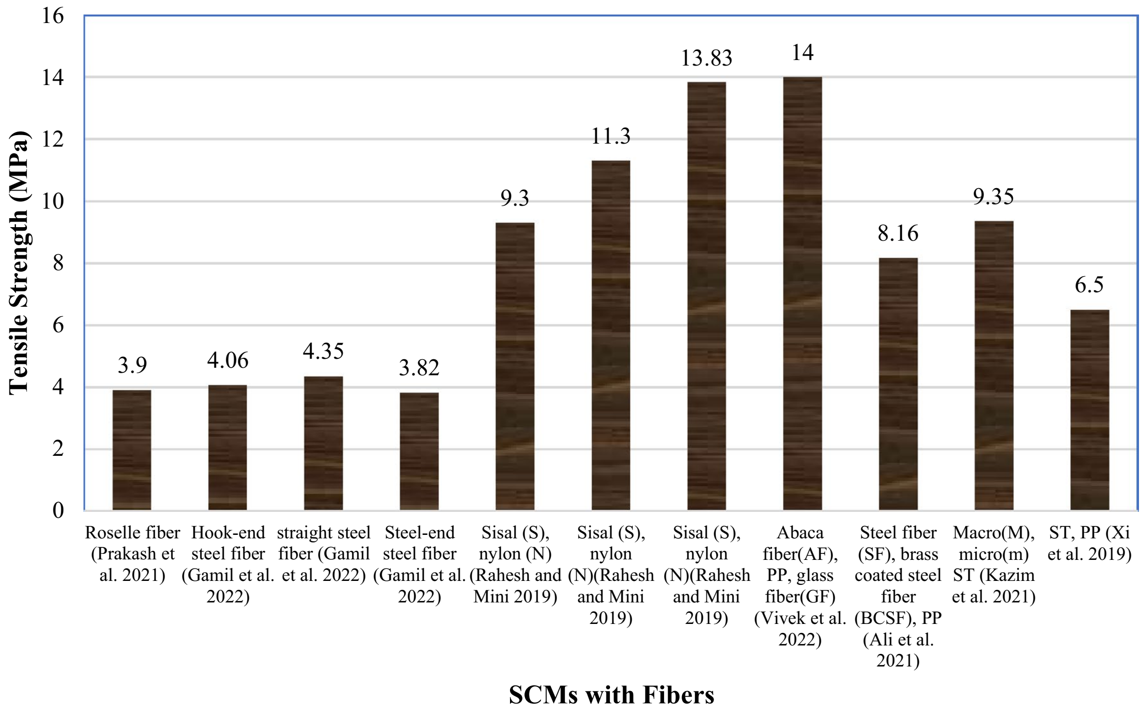


Fig. 14 Tensile strength for SCMs with fibers

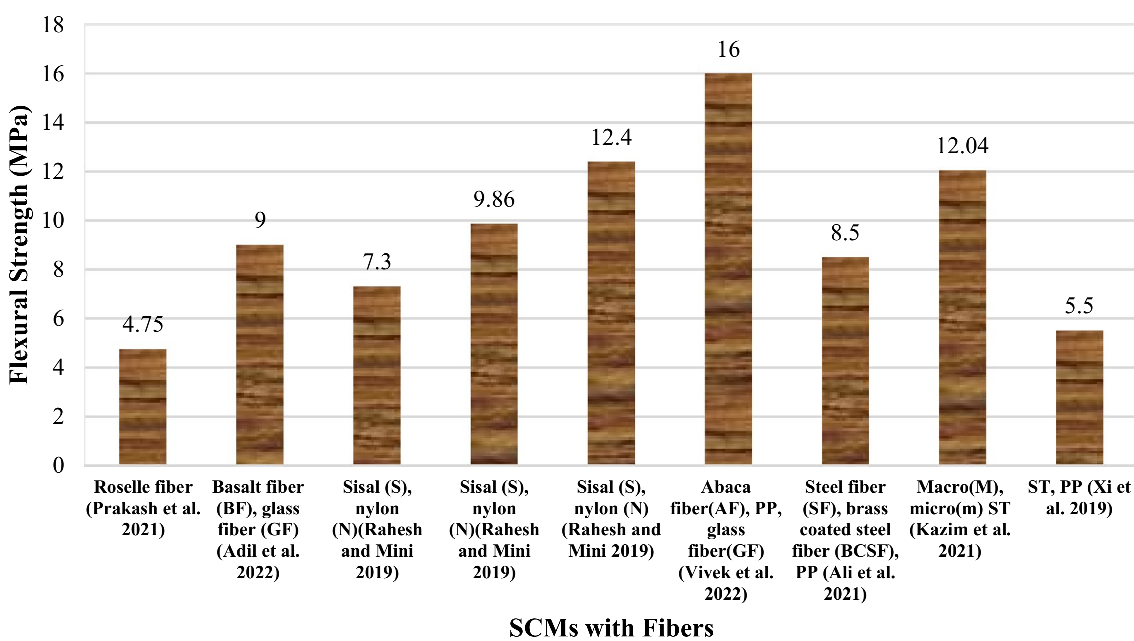


Fig. 15 Flexural strength for SCMs with fibers

acted as filler than the pozzolanic materials. So, the permeability was reduced, and enhanced the durability properties. From research, it is concluded that matrix densification improves durability, and alccofine-1203 improves durability. Since Al is less expensive than OPC, it was determined to be affordable. Some SCMs like HGM and RCP provided good fluidity and compressive strength but low durability was observed because of porosity (Veera 2021; Sergio et al.

2022). Whereas hydraulic lime, WMS addition acted as a filler and did not influence mechanical performance but it was very effective in restoring the alkalinity in the system thus reducing capillary absorption and carbonation depth (Rakesh et al. 2021). Carbonation diminishes the alkalinity and breaks the thin protective passive layer around the rebar resulting in rusting, increasing the curing duration, and reducing the carbonation depth (Rahul and Rizwan 2020). Free and chemically bound water was unable to vaporize away at high temperatures, which caused falls to accumulate on the surface, exposing the steel and reducing its durability in the high-densified concrete (Prithiviraj and Saravanan 2022). Sadrmomtazi et al. (2020) found that the effect of high temperature in steel fiber SCC, up to 200 °C the loss in mechanical strength is negligible because the crack is stopped by spalling when exposed to high temperature the fracture energy decreases. To solve this problem high melting point fibers like PP were used which form a channel to vaporize out the water so that it would not fall on the surface (Farhad et al. 2019). Xiliang et al. (2022) improved the residual strength and spalling resistance to 400 °C (elevated temperature) by incorporating SF and PF at low dosages. Vanesa et al. (2022) introduced metallic steel fiber and synthetic surface-dimpled polypropylene fiber its involvement demands more water to preserve the workability which results in porosity and significantly affects the freeze and thaw condition in concrete, the addition of a large amount of GGBS (70%) reduces the dragging capacity and increase the flexibility of the binder thus sustain the freeze and thaw phenomenon. SCC showed the same properties as NC in the case of low tensile strength and crack resistance. Therefore, to boost the post-peak performance of concrete, fibers were added. This resulted in a matrix density, which in turn decreased the water permeability in concrete. Thus, the corrosion resistance behaviour can be enhanced since it was considered the most detrimental behaviour in concrete structures. Civil engineers designed not only to improve strength but also durability with minimum maintenance. When steel was corroded the volume increased by six times approximately then caused failure. Before incorporating fibers inside the concrete, its resistance to alkaline environments had to be checked to make it durable for protecting the concrete, the feasible fiber was synthetic forta-ferro (SFF) which was 100% pure copolymer and non-corrosive (Aliha et al. 2018). Natural fibers affect durability because of hydrophilic and deteriorate due to a high water absorption rate, treating the fibers helps to overcome this. Synthetic fibers namely nylon fibers absorbed more water, whereas carbon fiber (CF) and AR glass fiber had nil absorption capacity. Hence in terms of durability nylon fibers had the least resistance to acid attack (Rahesh and Mini 2019). A significant benefit of natural fiber water absorption properties was examined by Dávila-Pompermayer et al. (2020) the addition of SCM enhances the packing density and avoids the ingress of any deleterious material but it also leads to the formation of shrinkage at early stages. Even when fibers are added, shrinkage can still occur. The amount of shrinkage depends on the length of the fibers employed, with long fibers often having a greater effect than short fibers (Ramkumar et al. 2020). Lechuguilla natural fiber from agave plants absorbs water 98% in a day and desorbs 14% the following day, considering this characteristic it has been utilized as an internal curing agent. As a result, drying shrinkage ranges from 42 to 14% for the period of 14 to 91 days. This clearly states that the free water evaporation unequivocally drops. Durability is enhanced by the addition of SCM in concrete but while adding fiber, the length and aspect ratio of fiber highly influence the absorption rate simultaneously with ultrasonic pulse velocity (UPV) which determines the density of the concrete (Akshay et al. 2021).

In summary, SCMs were widely used to improve durability resistance in concrete. For example, GGBS-based concrete was much beneficial for underground sewerage appurtenant structures, basements, and trenches where it resists the penetration of sulphates and their attacks. Similarly, most SCMs such as SF, MK, and FA when replaced partially by cement had improved the resistance against permeation, sorption, chloride, and water ingress (Vivek and Dhinakaran 2017a). However, when the fibers were added to concrete the durability point of view was resisted by the initiation, and propagation of cracks was controlled by bridging of fibers added to some extent. The durability resistance offered by fibers had fluctuations based on the type of fibers, such as metallic, non-metallic, synthetic, and natural fibers. The hydrophobic and hydrophilic nature of fibers is also significant to resist durability. For example, steel fibers used in concrete had better tensile characteristics than durability resistance in concrete. Hence, tensile strength resistance was enhanced by the addition of fibers only but the durability resistance was governed by most SCMs, however, in combinations with fibers would sound both strength and durability aspects.

5.4 Microstructure Studies

Microstructural studies were mostly used to find the behaviour of aggregate-paste and fiber-paste at the interface because ITZ is a thin layer outer to aggregate considered to be a critical zone as it contains more voids and high soluble CH in it which starts to fail (Wong et al. 2009). To improve the packing density, it is necessary to grade powder materials and aggregates properly. Around 70% of research works used an aggregate of size 16 and 20 mm but in FR-SCC, 10–12.5mm was feasible for good compatibility (Alsubari et al. 2018; Ramesh et al. 2020). Field Emission Scanning Electron Microscopy (FESEM), Optical Microscopy, Scanning Electron Microscope (SEM), Scanning Transmission Electron Microscopy, and Energy Dispersive X-ray spectroscopy (EDX) were used for the morphological analysis of the nature of fiber used in concrete (Sutapa et al. 2020). Understanding the adhesion behaviour of various types of fiber, particularly natural fibers, requires an intensive morphological investigation before the fiber is introduced. This is because the morphology of natural fibers varies adhering to alkaline, silane, and heat treatment (Rahesh and Mini 2019). Nursiah et al. (2022) noticed a significant improvement in the mechanical properties of SCC by doing an alkaline treatment of banana fiber by 0.12%. Treating the fibers affected the workability and bond strength but not their tensile strength (Sutapa et al. 2020) but Genbao et al. (2022) employed two different methods called ultrasonic vibration coating treatment (UVCT) method using nano-size silica sand and alkali activation treatment (AAT) method on jute fiber. The use of jute fiber reduces the flow nature but UVCT improves mix workability however it also enhances the bond between the fiber and the concrete matrix because of nano silica involvement in the hydration process through SEM and XRD results. Chenjie et al. (2023) used digital image analysis with microscopy for the study of the crack patterns that originated in the fibers-aggregates-cementitious matrix zone. Studying the crack patterns will reveal the fracture mechanism. To identify the fracture process zone in fiber and non-fiber reinforced beams with notches, Muhammed et al. (2023) used the DIC approach. SCMs were included to improve the compactness (Prithiviraj and Saravanan 2022), it is important to determine the composition of their chemicals. Consequently, X-ray Diffraction (XRD) and X-ray Fluorescence spectroscopy (XRF) techniques give information on the different phases in cement and hydrates, help identify crystal structures, describe hydration kinetics, and identify degradation effects like sulphate attack, delayed ettringite attack, thaumasite attack.

From the microstructural study, many research works explained the characteristics of SCMs. The information from the internal structure is used to understand the relation between the microscopic and macroscopic properties of concrete. For the powder gradation check, laser diffractometry was used. The chemical composition used to support the claim that the addition of SCM increases strength like how Choudhary et al. (2020) stated FA has a peak of Al_2O_3 content, exceeding the optimum range (35%) causing shrinkage. Slag has more silicon concentration than FA so its reactivity and rate of dissolution were high. Some materials like GGBS, SF, and LP have high calcium (CaO) and silica (SiO2) content and showed improved performance. Nowadays most of the research works use a processed form of GGBS called alccofine (Al) of ultrafine which is glassy, showed improved reactivity and strength (Bhanavath and Sivakumar 2021; Gupta et al. 2021; Ranjitha et al. 2021). RHA is a silica-based substance with a rough, amorphous texture that takes the form of cristobalite, limestone filler (LF) is crystalline, smooth, and finer than cement and MK (Thiago et al. 2022). Understanding the shape of the substance comes from the SEM image's morphology like MK is round in shape and rougher in texture which is rich in aluminosilicate (Gemma et al. 2022), and SS is dense and irregular in shape (Prarthita et al. 2021). Burcu and Mehmet (2018) checked the effectiveness of SF and MK using DTA, the CH consumption rate was higher in MK than in SF. Bassam et al. (2023) used ramen spectroscopy to identify the peak formation of C-S-H that explains the pozzolanic nature of the nano agricultural waste used to get ultra-high performance self-compacting concrete using nano sugar cane bagasse ash (NSCBA), nano cotton stalk ash (NCSA) and nano rice straw ash (NRSA) using dosages of 1%, 2%, and 3% respectively. For the powder gradation check, laser diffractometry was used. Moving towards the usage of wastes as SCMs: Using FPGC, Mugahed et al. (2022) discovered that the production of three different forms of CSH gel, namely fibrous, rosette, and granular, was what caused the effective bond. RCP paves the way to a sustainable environment, it improved strength but it demanded more SP because of the micro-pores present inside (Veera 2021). Imane et al. (2022) used SEM results to find the refinement level when adding construction and demolition waste in SCC, from XRD it was discovered that the hydration product production is delayed. Mara et al. (2022) confirmed the incorporation of MGW which is crystalline with less pozzolanic effect and the finest among all SCMs, does not influence the density factor but acts as a filler and disconnects the concrete pores, silicon, and aluminium oxides where the peak compounds. Sergio et al. (2022) worked on HGM was rich in oxides of silica and calcium was perfectly spherical and thus improved flowability enormously. Thus, under the same kind of SCMs, the chemical composition could differ because of the variation in ore formation.

5.5 Influence of Recycled Fibers

In concrete, the waste glass powder was used as a fine aggregate replacement up to 15% and reinforced with recycled steel fibers up to 1.5%. It was reported that the mechanical properties of concrete were highly influenced by 9% of waste glass powder with 1% recycled steel fibers (Mavoori et al. 2021). The influence of recycled glass fiber-reinforced polymer was studied through mechanical and durability tests. It was reported that the influence of 5% weight of the coarse aggregate replacer as recycled GFRP has shown descending compressive strength but tensile strength has improved (Alireza et al. 2017). The mortars were developed by conditioned/unconditioned secondary waste carbon fibers from the industrial recycled fibers with nano clay for uniformity of fiber matrices. The authors reported that combinations of conditioned carbon fibers with nano clay have improved compressive strength by 13% and flexural strength by 76% concerning control mixes (Matteo et al. 2023). The addition of recycled carbon fiber-reinforced polymer in cementitious composites has shown a reduction in workability beyond 0.25%. However, the mechanical properties were influenced in the range of 0.25–1% of recycled CFRP developed as a sustainable material (Aamar et al. 2022). The influence of waste cellulose fibers in cementitious composites has shown improved flexural strength and energy absorption capacity in mortars at early ages catered to the effect of autogenous shrinkage (Mohammad et al. 2023a).

6 Future Scope-Based on Authors Contribution

6.1 Binary Blend SCC

The depletion of global warming and environmental abiotic depleting perspective was seen due to the addition of SCMs in terms of replacing the cement in the construction sector. In the early stages, more effort went into focusing on the binary mix to improve the characteristics by adding SCM because SCC required a higher powder content and thus lower cement proportion. Fly ash (FA) was implemented in place of cement by Vivek and Perumal (2013) from 25 to 50% as a partial substitute for cement in SCC. Anjali et al. (2015) researched the compressive and split tensile strength of MK-based SCC mixes and reported that MK performed better than NC. Vivek and Dhinakaran (2015) concluded that silica fume as a binary blend in SCC has improved fresh and mechanical properties. Vivek and Dhinakaran (2017a, b, 2022), researched SCC using SCMs Viz. SF, MK, and GGBS as a partial substitute for cement in binary forms. It was reported by authors that the use of SCMs had improved fresh, mechanical, and durability properties. A specific mention is that the GGBS-based SCC mix was found to be cost-effective among other SCMs-based SCC mixes as one of the sustainability indicators measured. Subramanian and Govindasamy (2017) determined the high strength SCC of grade M60 by replacing cement with MK from 5% to 20%, compressive strength was enhanced at 20% replacement but split tensile strength was enhanced at 10% replacement for practical applications like members where compression predominates like columns, foundation there 20% MK can be used whereas members like slab, beams where tension or flexure predominates there 10% MK can be used. Marshaline Seles et al. (2017) compared the performance of ternary blended SCC beams using SF and MK. It was reported that flexural behaviour and ductility were more pronounced in the ternary SCC beams compared to the control SCC and conventional RCC beams.

6.2 Ternary Blend SCC

Vivek (2022) studied the performance of SCC by industrial waste GGBS (30–50%) and MK (5–15%) in ternary form, resulting in improved compressive and tensile strength than NC and control SCC. Aysha and Vivek (2021) introduced the agricultural waste RHA with SF, and MK in ternary form was investigated for the behaviour of SCC in terms of microstructural properties, fresh properties, and mechanical properties. It was reported that RHA and MK-based ternary SCC mixes surpassed control SCC. Vivek et al. (2017) worked on the ternary mix with two different combinations MK+GGBS and SF+GGBS and found that the flexural and ductility behaviour of the SCC beams were more effective than conventional vibrated concrete and control SCC concrete.

6.3 SCC Using Metallic Fibers

Lakman Prabu and Vivek (2020) investigated the behaviour of SCC with the addition of steel fibers (0–2%) and lathe waste (stainless steel crap waste) as fibers (constant 0.125%) in hybrid form; even though steel fibers addition reduces the flow in concrete but its optimum usage enriches the strength by 1.4 times.

6.4 SCC Using Non-Metallic Fibers/Natural Fibers

Vivek et al. (2022, 2023) experimented using non-metallic SCC by partially replacing the cement with metakaolin (20%) and alccofine (15%). Non-metallic fibers like abaca fiber (0.25–0.75), polypropylene fiber (0.5–2%), and glass fibers (0.5–2%) were incorporated as shown in Figs. 16, 17, 18. The ill effects faced by fibers in fresh properties were compensated by SCMs like MK and alccofine as the voids were reduced. The key objective of this effort was to establish how natural fibers can coexist with non-metallic fibers without losing their characteristics. According to SEM examination, the hybrid fiber combination strongly occupied the pores, enhancing the durability of the concrete. Although natural fibers don't make SCC more corrosive, their hydrophilic character does alter SCC strength. For this reason, Vivek and Prabalini (2021) performed different types of treatment on coconut fibers and resulted in chemical treatment of fibers was found to be effective. Thus chemical treatment of coconut fibers with SCMs had improved fresh, mechanical, and durability properties of SCC was reported by authors.

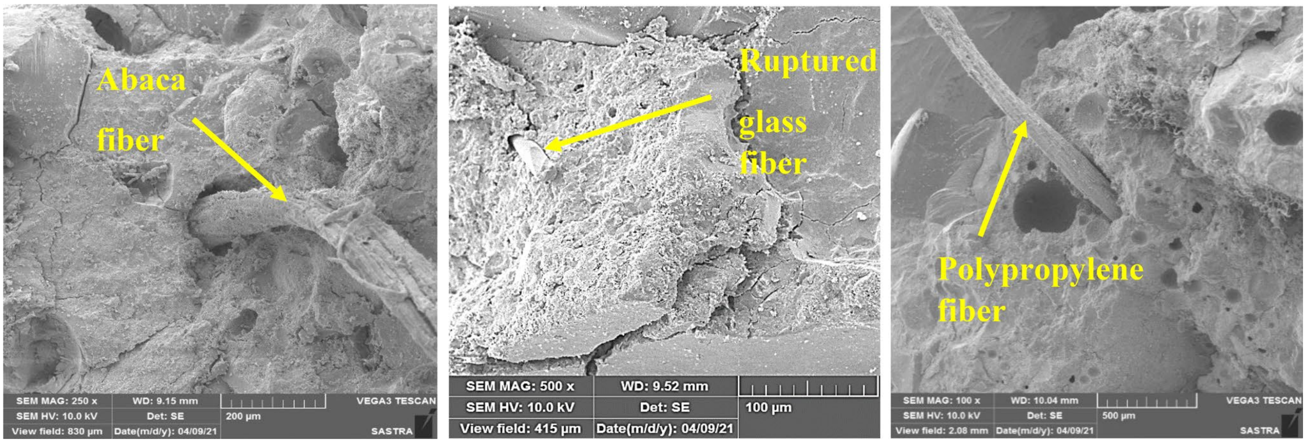


Fig. 16 SEM image of Fiber reinforced SCC (Vivek et al. 2022)

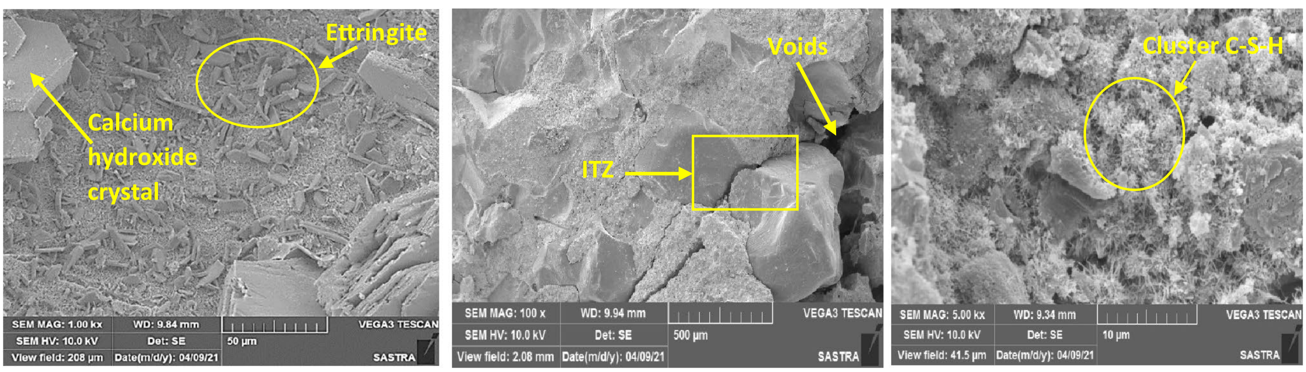


Fig. 17 SEM image of hydration products of Conventional SCC (Vivek et al. 2023)

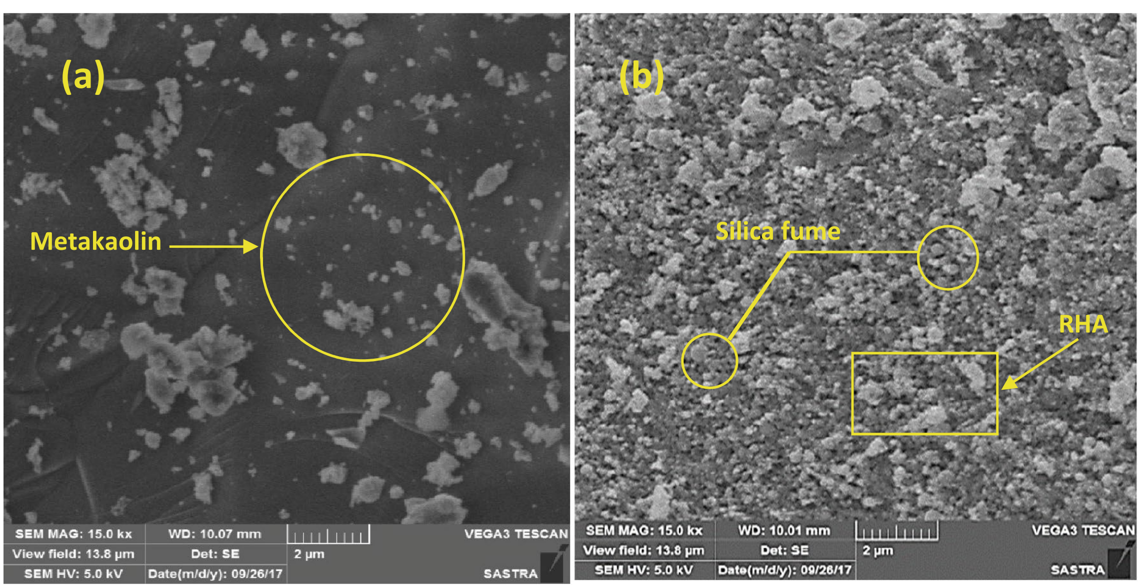


Fig. 18 SEM image of SCM (Vivek and Dhinakaran 2022) **a** Metakaolin **b** Silica Fume and Rice Husk Ash

From the available research works, the future scope of SCMs in SCC will be on the sustainable indicators namely environmental impact, societal, and economy. This will be achieved through the incorporation of tailor-made SCMs based on the chemical compositions irrespective of binary, ternary, quaternary, and poly-blend forms. Among the different fiber additions, the degradation effects of natural fibers by blending with hybrid combinations of metallic/non-metallic/synthetic fibers would result in enhanced tensile and flexural performance characteristics.

7 Conclusions

From the systematic review of the literature conducted in SCC using SCMs and fibers, the following conclusions are drawn:

- *Materials used* The transition from the conventional SCMs to the contemporary SCMs will be the scope for future research on the materials used in SCC. Since SCC requires more fines as a binder/fine aggregate replacement employing contemporary SCMs as a sustainable material is suggested.
- *Mix design* The repeated laboratory trials performed to arrive at optimum SCC mixes would be curtailed by suggesting the characterization of the rheological properties through computational fluid dynamics simulation techniques, which could minimize waste management as an environmental impact.
- *Fresh properties* The water demand and surface area of SCMs and fibers were the vital factors governing SCC fresh properties by yield stress and plastic viscosity. The contemporary SCM namely HGM can be utilized as a replacement for FA because it also uses the ball bearing effect to improve the flow nature. Similarly, MGW decreases the amount of water absorbed by nature, enhancing the flow nature of SCC. In terms of workability, macro fibers improve workability more than micro fibers. Nevertheless, the entangling of fibers affects the flowability but this can be neutralized by the addition of SCMs like VPP, Al.
- *Mechanical properties* Like FA, GFNS also delayed the early strength because of its low calcium content. However, the introduction of graphene oxide can counteract this effect. From a broad perspective, long fibers improve compressive strength because short fibers don't have a homogenized mix. Hybrid fiber mixes performed better flowability and mechanical strength like flexure, fracture toughness, and deflection capacity than the mono fiber additions. Recent research focuses on Shape Memory Alloy as its flexural strength was thrice the polypropylene fiber and twice the steel fiber, and its deflection was twice the polypropylene fiber and four times the steel fiber. Hence, the flexural strength and fracture toughness were greater in SMA.
- *Durability properties* SCMs that were rich in silicon content contributed to high reactivity like slag, FPGC, SF, RHA, etc., and provided good strength to the concrete. The Al_2O_3-rich minerals like FA, HGM, and MK enhanced the durability behaviour by restricting the chloride ion ingress. The flexible and CF and AR glass fibers are also preferable due to nil absorption capacity. While metallic fibers were superior to all other fibers in terms of tensile strength, synthetic fibers are superior to steel fibers from the perspective of ductility. The main drawback of ST is the development of corrosion in concrete, hence fibers like FRR that are naturally non-corrosive are preferred. PP fibers are used in the majority of elevated temperature applications because they are beneficial against the spalling effect. Natural fibers, such as basalt fiber, can endure temperatures of up to 300°C before turning more brittle.
- *Microstructure properties* The use of SCMs in SCC leads to the formation of dense supplementary C-S-H gel compounds and their derivatives during hydrated phases by reserving more calcium content to deliver the end crystalline products. Moreover, the pore size refinement and strengthening of ITZ took place by the combinations of SCMs and fibers.
- *Sustainability* Natural fiber additions in SCC as a sustainable eco-friendly material due to its hydrophilic nature absorbing more water and abrupt flow was suggested for chemical treatment of fibers with the addition of HRWR was preferred. Alkaline treatment, which is often employed, was less effective than treating the fibers in a permanganate solution.
- *Limitations* The limitations of the study include less number of analytical and numerical frameworks reviewed when compared with the experimental investigations conducted with conventional and modern SCMs. The influence of different fibers was studied on SCC and few works on recycled fibers were highlighted.
- *Potential future lines of research* The incorporation of SCMs in SCC are formulated as tailor-made products based on the chemical compositions namely calcium, silica, alumina, etc. on their SCMs homogeneous group. In mono/hybrid combinations of fibers, the treated natural fibers combined with metallic/non-metallic/synthetic fibers would prevent the degradation effects of natural fibers. Hence in SCC, the blend of tailor-made SCMs with treated natural fiber combinations would result in a sustainability perspective.

Author contributions S- prepared the manuscript by the collection of literature, preparation of tables and figures S.S- Checked the manuscript and made corrections. Microstructure studies were formulated and performed Grammarly and Turn it in Plagiarism checks and Revision for the manuscript based on the reviewer's comments received was carried out.

Declarations

Conflict of interest The authors declare no competing interests.

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