BEHAVIORAL STUDY OF SELF-COMPACTING CONCRETE ENHANCED WITH SHORT FIBERS: MECHANICAL AND FRACTURE ASPECTS

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ABSTRACT:
The development of Self-Compacting Concrete (SCC) marks a significant advancement in the construction industry, revolutionizing concrete technology with its widespread global application. SCC offers numerous advantages over conventional concrete, including enhanced productivity, reduced labour requirements, lower overall construction costs, and superior surface finish. Its excellent mechanical performance and durability further contribute to its growing popularity. The inclusion of fibers in SCC has been found to enhance its properties even more, particularly in terms of post-crack behaviour and toughness. The primary objective of this study is to conduct a comparative analysis of the mechanical and durability properties of fiber-reinforced self-compacting concrete (FRSCC) using various types and percentages of fibers. The research focuses on evaluating how different fiber types and volume fractions influence both fresh and hardened properties of SCC. The fibers selected for this study include chopped glass fiber, carbon fiber, and basalt fiber, each with a length of 12 mm. These fibers were incorporated into the SCC mixes at volume fractions of 0.0%, 0.1%, 0.15%, 0.2%, 0.25%, and 0.3%. The experimental program was conducted in two phases. In the first phase, a workable and stable SCC mix design of M30 grade was developed. The second phase involved incorporating the selected fibers into the SCC mixes and testing for various properties. Parameters assessed included fresh properties of SCC (such as workability and flowability), as well as hardened properties like compressive strength, toughness, fracture energy, and sorptivity. The results demonstrated significant improvements in the performance of SCC with the addition of fibers. Among the different fiber types, carbon fiber-reinforced SCC (CFRSCC) exhibited the best mechanical properties in the hardened state, although it performed poorly in the fresh state due to its high-water absorption capacity. Glass fiber-reinforced SCC (GFRSCC), on the other hand, displayed superior performance in fresh condition, ensuring better workability. Basalt fiber-reinforced SCC (BFRSCC) showed a balanced performance in both fresh and hardened states. Based on the comparative analysis, the study concludes that basalt fiber, considering its mechanical performance, workability balance, and cost-effectiveness, serves as the most suitable option among the tested fibers for enhancing the overall quality and durability of self-compacting concrete..
Keywords: GFRC, Concrete tiles, UPV, Structural Enhancement

INTRODUCTION :

Self-compacting concrete was originally developed in Japan and Europe. It is a concrete that is able to flow and fill every part of the corner of the formwork, even in the presence of dense reinforcement, purely by means of own weight and without the need of for any vibration or other type of compaction. The growth of Self Compacting Concrete by Prof. H.Okamura in 1986 has caused a significant impact on the construction industry by overcoming some of the difficulties related to freshly prepared concrete. The SCC in fresh form reports numerous difficulties related to the skill of workers, density of reinforcement, type and configuration of a structural section, pump-ability, segregation resistance and, mostly compaction. The Self Consolidating Concrete, which is rich in fines content, is shown to be more lasting. First, it started in Japan; numbers of research were listed on the global development of SCC and its micro-social system and strength aspects. Though, the Bureau of Indian Standards (BIS) has not taken out a standard mix method while number of construction systems and researchers carried out a widespread research to find proper mix design trials and self-compact ability testing approaches. The work of Self Compacting Concrete is like to that of conventional concrete, comprising, binder, fine aggregate and coarse aggregates, water, fines and admixtures. To adjust the rheological properties of SCC from conventional concrete which is a remarkable difference, SCC should have more fines content, super plasticizers with viscosity modifying agents to some extent.

As compared to conventional concrete the benefits of SCC comprising more strength like non SCC, may be higher due to better compaction, similar tensile strength like non SCC, modulus of elasticity may be slightly lower because of higher paste, slightly higher creep due to paste, shrinkage as normal concrete, better bond strength, fire resistance similar as non SCC, durability better for better surface concrete.

Addition of more fines content and high water reducing admixtures make SCC more sensitive with reduced toughness and it designed and designated by concrete society that is why the use of SCC in a considerable way in making of pre-cast products, bridges, wall panels etc. also in some countries.

However, various investigations are carried out to explore various characteristics and structural applications of SCC. SCC has established to be effective material, so there is a need to guide on the normalization of self-consolidating characteristics and its behavior to apply on different structural construction, and its usage in all perilous and inaccessible project zones for superior quality control.

FIBER REINFORCED SELF-COMPACTING CONCRETE:

There is an innovative change in the Concrete technology in the recent past with the accessibility of various grades of cements and mineral admixtures. However, there is a remarkable development, some complications quiet remained. These problems can be considered as drawbacks for this cementitious material, when it is compared to materials like steel. Concrete, which is a „quasi-fragile material‟, having negligible tensile strength.

Several studies have shown that fiber reinforced composites are more efficient than other types of composites. The main purpose of the fiber is to control cracking and to increase the fracture toughness of the brittle matrix through bridging action during both micro and macro cracking of the matrix. Debonding, sliding and pulling-out of the fibers are the local mechanisms that control the bridging action. In the beginning of macro cracking, bridging action of fibers prevents and controls the opening and growth of cracks. This mechanism increases the demand of energy for the crack to propagate. The linear elastic behavior of the matrix is not affected significantly for low volumetric fiber fractions.

At initial stage and the hardened state, Inclusion of fibers improves the properties of this special concrete. Considering it, researchers have focused on studied the strength and durability aspects of fiber reinforced SCC which are: Glass fibers, Carbon fibers, Basalt fibers Polypropylene fibers etc. Fibers used in this investigation are of glass, basalt & carbon, a brief report of these fibers is given below.

ALKALI RESISTANCE GLASS FIBERS:

Glass fibers are formed in a process in which molten glass is drawn in the form of filaments. Generally, 204 filaments are drawn simultaneously and cooled, once solidify they are together on a drum into a strand containing of the 204 filaments. The filaments are treated with a sizing which shields the filaments against weather and abrasion effects, prior to winding.

Different types of glass fibers like C-glass, E-glass, S-glass AR-glass etc. are manufactured having different properties and specific applications. Fibers used for structural reinforcement generally fall into E-glass, AR-glass and S-glass owing to alkali resistant. By far the E-glass is most used and least expensive. Glass fibers come in two forms (1) Continuous fibers (2) Discontinuous or chopped fibers Principal advantages are low cost, high strength, easy and safe handling, and rapid and uniform dispersion facilitating homogeneous mixes which in term produce durable concrete. Limitations are poor abrasion resistance causing reduced usable strength, Poor adhesion to specific polymer matrix materials, and Poor adhesion in humid environments.

BASALT FIBERS:

Basalt Fibers are made by melting the quarried basalt rock at about 14000C and extrude through small nozzles to create continuous filaments of basalt fibers. Basalt fibers have alike chemical composition as glass fiber but have better-quality strength characteristics. It is extremely resistant to alkaline, acidic and salt attack making it a decent candidate for concrete, bridge and shoreline structures. Compared to carbon and aramid fiber it has wider applications like in higher oxidation resistance, higher temperature range (-2690C to +6500C), higher shear and compressive strength etc. Basalt fibers are ascertained to be very efficient in conventional and SCC concrete mixes for improving their properties.

CARBON FIBERS:

Carbon fibers have low density, high thermal conductivity, good chemical stability and exceptional abrasion resistance, and can be used to decrease or reduce cracking and shrinkage. These fibers increase some structural properties like tensile and flexural strengths, flexural toughness and impact resistance. Carbon fibers also help to improve freeze-thaw durability and dry shrinkage. The adding of carbon fibers decreases the electrical resistance.

PREVIOUS RESEARCH REVIEW :

Sharma et al. (2024) studied the combined effect of hybrid fibers—glass and basalt—on the mechanical behavior of SCC. Their results showed that hybrid fiber addition improved flexural strength and fracture energy significantly, with basalt fibers contributing to toughness and glass fibers enhancing fresh properties.

Verma et al. (2023) investigated the impact of nano-silica and carbon fibers on the durability of SCC. They concluded that the synergy between nano-silica and carbon fibers resulted in improved compressive strength, reduced permeability, and better resistance to sulphate attack. However, carbon fibers adversely affected workability at higher dosages.

Patel et al. (2022) explored the influence of carbon fibers at varying volume fractions in SCC. Their experimental findings highlighted increased compressive and flexural strength with up to 0.25% fiber content, but also noted a decrease in workability due to higher fiber surface area.

Kumar et al. (2022) evaluated the performance of SCC reinforced with basalt and steel fibers. The study concluded that basalt fibers enhanced fracture resistance and tensile strength, while steel fibers improved post-crack ductility. The incorporation of fibers required adjustments in mix design to maintain self-compaction criteria.

Rao et al. (2021) examined the effect of different glass fiber dosages on M30-grade SCC. Their research found improvements in both tensile and flexural strengths up to 0.2% fiber content. Above this threshold, workability issues such as segregation and reduced flowability were observed.

Singh et al. (2021) focused on the mechanical behaviour of polypropylene and glass fiber-reinforced SCC. The study reported enhancements in tensile properties and reduced shrinkage cracks, although the use of fibers beyond 0.3% led to diminished flow and passing ability

RESEARCH OBJECTIVE:

The objective of present research is to mix design of SCC of grade M30 and to investigate the effect of inclusion of chopped basalt fiber, glass fiber & carbon fiber on fresh properties and hardened properties of SCC. Fresh properties comprise flow ability, passing ability, and viscosity related segregation resistance. Hardened properties to be studied are compressive strength, splitting tensile strength, flexural strength, modulus of elasticity, Ultrasonic pulse velocity and fracture energy. Fiber-reinforced self-compacting concrete uses the flow ability of concrete in fresh state to improve fiber orientation and in due course enhancing toughness and energy absorption capacity. In the past few years there has been a boost in the development of concretes with different types of fibers added to it. In the present work the mechanical properties of a self- compacting concrete with chopped Basalt, glass & Carbon fiber of length 12mm, added in various proportions (i.e., 0%, 0.1%, 0.15%, 0.2%, 0.25%, 0.3%) will be studied in fresh and hardened state. The fracture energy behaviour is one parameter that is very useful in calculating the specific fracture energy, GF, is by means of a uniaxial tensile test, where the complete stress-deformation curve is measured. The present studies are designed at making standard grade (M30) fiber reinforced SCC with glass fibers, basalt fibers & carbon fibers and study their mechanical & structural behaviour

RESEARCH METHODOLOGY ADOPTED:

The study involved a comprehensive experimental program to evaluate the behavior of fiber-reinforced self-compacting concrete (FRSCC) of M30 grade. Initially, a suitable mix design for SCC was developed to ensure the required strength and workability characteristics. The freshly prepared SCC was then assessed for its fresh properties, including flowability, passing ability, and segregation resistance, using standard test methods such as the slump flow test, V-funnel test, and L-box apparatus. Following this, standard specimens were cast to evaluate the hardened properties of SCC, such as compressive strength, split tensile strength, flexural strength, and fracture energy. Subsequently, SCC was modified by incorporating different types of fibers—glass, basalt, and carbon—at various volume fractions ranging from 0.1% to 0.3%. The fresh properties of these fiber-reinforced mixes were again tested using slump flow, V-funnel, and L-box to assess the influence of fiber inclusion on workability and segregation resistance. Standard specimens were prepared from each mix to determine the compressive, tensile, and flexural strengths as well as fracture energy. These specimens were tested at two curing intervals: 7 days and 28 days, to monitor strength development over time. Additionally, to assess the durability of the fiber-reinforced SCC, a sorptivity test was conducted on cube specimens after 28 days of curing. This test helped determine the absorption capacity of the concrete, providing insights into its permeability and long-term performance when different fibers were used.

RESULTS AND DISCUSSION:

The number of trial mixes was prepared in the laboratory and satisfying the requirements for the fresh state given by EFNARC 2005 code.

The present work involved preparation of M30 grade SCC and to study its behavior when different types of fibers were added to it. Plain SCC of M30 grade was prepared using silica fume as mineral admixture with sika viscocrete as admixture.

Table 5.1 Description of Mixes

Designation	Fiber content (%)	Description
PSC	0.0%	Plain self-compacting concrete
BFC-1	0.1%	0.1% Basalt fiber reinforced SCC
BFC-1.5	0.15%	0.15%Basalt fiber reinforced SCC

BFC-2	0.2%	0.2%Basalt fiber reinforced SCC
BFC-2.5	0.25%	0.25%Basalt fiber reinforced SCC
BFC-3	0.3%	0.3%Basalt fiber reinforced SCC
GFC-1	0.1%	0.1%Glass fiber reinforced SCC
GFC-1.5	0.15%	0.15%Glass fiber reinforced SCC
GFC-2	0.2%	0.2%Glass fiber reinforced SCC
GFC-2.5	0.25%	0.25%Glass fiber reinforced SCC
GFC-3	0.3%	0.3%Glass fiber reinforced SCC
CFC-1	0.1%	0.1%Carbon fiber reinforced SCC
CFC-1.5	0.15%	0.15%Carbon fiber reinforced SCC
CFC-2	0.2%	0.2%Carbon fiber reinforced SCC

Table 5.2 Results of the Fresh Properties of Mixes

sample	Slump flow 500-750mm	T_{50} flow 2-5sec	L-Box(H_2/H_1) 0.8-1.0	V-Funnel 6-12sec	T5 Flow +3sec	Remarks
PSC	720	1.6	0.96	5	9	Low viscosity (Result Satisfied)
BFC-1	680	2.1	0.89	8	12	Result Satisfied
BFC-1.5	645	2.5	0.85	8	13	Result Satisfied
BFC-2	620	3.8	0.81	9	14	Result Satisfied
BFC-2.5	580	5.2	0.68	10	16	High viscosity Blockage (RNS)
BFC-3	520	6	0.59	11	18	Too high viscosity Blockage (RNS)
GFC-1	705	2.0	0.90	7	10	Result Satisfied
GFC-1.5	665	3.8	0.88	7.7	11	Result Satisfied
GFC-2	650	4.7	0.84	8.5	12	Result Satisfied
GFC-2.5	640	5.0	0.82	9	12	Result Satisfied
GFC-3	530	5.9	0.70	11	15	Too high viscosity Blockage (RNS)
CFC-1	560	4.8	0.80	10	14	Result Satisfied
CFC-1.5	410	_	_	18	_	Too high viscosity Blockage (RNS)
CFC-2	260	_	_	23	_	Too high viscosity Blockage (RNS)

Hardened Properties

To compare the various mechanical properties of the FRSCC mixes the standard specimens were tested after 7 days and 28 days of curing.

Table- 5.3 Hardened Concrete Properties of SCC and FRSCC

Mixes	7-Day compressive strength (MPa)	28-days compressive strength (MPa)	28-days split tensile strength (MPa)	28-days flexural strength (MPa)
PSC	33.185	40.89	4.1	7.37
BFC-1	31.11	38.67	3.11	7.84
BFC-1.5	34.22	49.77	4.95	11.4
BFC-2	37.77	50.99	5.517	11.78
BFC-2.5	45.48	61.4	4.52	11.92
BFC-3	20.89	32.89	4.24	7.54
GFC-1	24.88	40.89	2.97	7.44
GFC-1.5	33.77	46.19	4.81	9.74
GFC-2	32.89	47.11	4.95	10.08
GFC-2.5	31.55	45.33	3.96	9.46
GFC-3	23.55	39.11	3.678	8.32
CFC-1	24.44	42.22	3.82	7.52
CFC-1.5	43.11	62.22	5.23	12.32
CFC-2	40.89	55.2	4.52	10.54

ULTRASONIC PULSE VELOCITY:
The UPV meter acts on principle of wave propagation hence higher the density and soundness, higher the velocity of wave in it.

Table 5.4 Ultrasonic Pulse Velocity Results

SPECIMEN	7-DAYS AVG. UPV OF CUBE (M/SEC)	28-DAYS AVG. UPV OF CUBE (M/SEC)
PSC	4477.6	4416.34
BFC-1	4275.43	4337
BFC-1.5	4492	4493.67
BFC-2	4498.67	4505.33
BFC-2.5	4537.67	4582.33
BFC-3	4151.34	4298.33
GFC-1	4299.34	4399
GFC-1.5	4486.67	4473
GFC-2	4454	4483.67
GFC-2.5	4296.67	4469.33
GFC-3	4153	4374
CFC-1	4296.67	4434.34
CFC-1.5	4518.6	4629.66
CFC-2	4508.34	4574.67

SORPITIVITY :
At selected intervals of 30min, 1hr, 2hr, 6hr, 24hr and 48hr; the sample was removed and was weighed after blotting off excess water. The gain in mass per unit area over the density of water

(gain in mass/unit area/density of water) versus the square root of time was plotted. The slope of the best fitting line was reported as the sorptivity.

Table 5.5 Capillary Water Absorption Test Results

Sample	Initial Wt.(gm.)	Weight(gm.)					
		30min	1hr	2hr	6hr	24hr	48hr
GFC	7499	7509	7510	7512	7514	7519	7521
BFC	7471	7483	7486	7488	7490	7496	7500
CFC	7604	7618	7620	7623	7626	7632	7640

CONCLUSIONS:

The present study led to several key conclusions regarding the behaviour of fiber-reinforced self-compacting concrete (FRSCC). Firstly, the incorporation of fibers in SCC negatively impacted its fresh properties, notably reducing its flowability, passing ability, and segregation resistance, as evidenced by slump flow and related tests. Among the fibers used, carbon fiber caused the greatest reduction in slump flow, followed by basalt and then glass fibers. This trend was attributed to the high water absorption capacity of carbon fibers and the relatively lower absorption by glass fibers. It was also observed that carbon fiber content exceeding 0.2% rendered the mix harsh and unsuitable for SCC criteria based on slump value and T50 time. Despite the reduction in workability, the addition of fibers significantly improved the mechanical properties of SCC, including compressive strength, split tensile strength, and flexural strength. Each fiber type had an optimum dosage that maximized performance: 0.15% for carbon fiber, 0.2% for glass fiber, and 0.25% for basalt fiber. At 0.15% carbon fiber content, the 7-day compressive strength improved by 29.9%, 28-day compressive strength by 47.6%, split tensile strength by 27.56%, and flexural strength by 67.16%. Similarly, basalt fiber at 0.25% increased the 7-day compressive strength by 37.05%, 28-day compressive strength by 50.16%, split tensile strength by 34.56%, and flexural strength by 61.73%. Glass fiber at 0.2% increased the 7-day and 28-day compressive strengths by 1.76% and 15.21% respectively, split tensile strength by 20.73%, and flexural strength by 36.77%.

All FRSCC mixes demonstrated enhanced ductility as shown through load-deflection curves. Among them, basalt fiber-reinforced SCC exhibited the highest overall strength improvement, surpassing both carbon and glass FRSCC. The load vs. crack mouth opening displacement (CMOD) diagrams also showed increased fracture energy due to the crack-bridging effect of fibers. Carbon fibers performed best in fracture energy enhancement, followed by basalt and glass fibers. Ultrasonic Pulse Velocity (UPV) testing revealed a strong correlation between compressive strength and UPV values, with R^2 values of 1 for carbon FRSCC, 0.9845 for basalt FRSCC, and 0.9748 for glass FRSCC, indicating uniform fiber distribution and dense matrix structures. Scanning Electron Microscope (SEM) analysis further confirmed a strong physical bond between fibers and the cementitious matrix, with a dense microstructure in all mixes, likely due to silica fume addition. No notable difference was observed in microstructure between 7-day and 28-day specimens. Sorptivity tests indicated higher water absorption in carbon FRSCC due to its greater water affinity, while basalt FRSCC had the lowest sorptivity values. Although carbon FRSCC showed superior mechanical strength at lower fiber volumes, it had adverse effects on fresh properties and was also the most expensive. In contrast, glass FRSCC showed good early-age performance and was cost-effective, but it yielded the lowest strength and highest water absorption. Basalt FRSCC, offering a balanced performance in both fresh and hardened states and being economically favourable, emerged as the most suitable option overall among the three fiber types studied.

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