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INFLUENCE OF MACRO SYNTHETIC FIBERS ON MECHANICAL PROPERTIES OF BINARY CONCRETE CONTAINING GROUND GRANULATED BLAST FURNACE SLAG AND FLY ASH

M. VENKATA MAHESWARA REDDY
Research Scholar, Department of Civil Engineering, Jawaharlal Nehru Technological University, Anantapur (JNTUA), Ananthapuramu - 515002, Andhra Pradesh, India. Email: mvmreddy54@gmail.com

S. KRISHNAIAH
Professor, Department of Civil Engineering, Jawaharlal Nehru Technological University, Anantapur (JNTUA), Ananthapuramu - 515002, Andhra Pradesh, India.

Abstract

Concrete production involves using vast quantities of ordinary portland cement (OPC), the primary binder material. However, OPC production uses high embodied energy and emits more CO_2 into the atmosphere. One of the alternatives is using industrial waste or byproducts such as fly ash (FA) and ground granulated blast furnace slag (GGBS) as supplementary cementitious material. However, the main drawbacks of conventional concrete with or without supplementary cementitious material are its brittleness and lower elasticity. This led to the addition of fibers to concrete. In this study, the effects of macro synthetic fibers (MSF), 20% FA class F, and 20%, 25%, 30%, 35%, and 40% GGBS were used as supplementary cementitious materials to produce MSF-reinforced binary concrete of grade 40 MPa. MSF of aspect ratio 36 was added to the mix at 0%, 0.25%, 0.5%, 1%, 1.5%, and 2% by volume fraction. The results showed that the MSF fiber-reinforced binary workability decreased with an increase in the addition of MSF. SP22 (i.e., 1.5% MSF, 20% FA, 30% GGBS) specimens yield good results, and higher strength. Furthermore, the mechanical performance of all samples improved significantly with an increase in the percentage of the volume of MSF. Incorporating MSF, GGBS, and FA reduces OPC usage, enhances strength characteristics, and contributes to cost reduction in construction.

Indexterms: Macro Synthetic Fibers, Fly Ash, Ground-Granulated Blast Furnace Slag, Mechanical Properties, Supplementary Cementitious Material, Cracking, Ordinary Portland Cement.

1. INTRODUCTION

Concrete plays a crucial global significance as a construction material. The booming infrastructure and progress have resulted in a surge in construction activities, thus driving up the need for ordinary portland cement (OPC). In order to fulfil the demand for OPC, there has been significant production growth. However, this has resulted in a substantial depletion of resources for the cement industry and a global emission of 5–7% of CO_2[1]. The maximum strength of regular OPC relies on the creation of C-S-H gel through the cement hydration process[2–5]. Therefore, in modern technology, different materials have been chosen to achieve the necessary durability of concrete, substituting cement. Conversely, growing industrialization has resulted in a significant quantity of industrial waste being produced. These waste materials need significant quantities of area for disposal or various treatment procedures to be effectively utilized. Therefore, including these waste products in the concrete production process while considering their

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properties can effectively decrease the environmental impact, waste management expenses, and concrete manufacturing costs[6–9].

The current study incorporates waste materials from the iron industry and thermal power plants, commonly referred to as ground-granulated blast furnace slag (GGBS) and flyash (FA)[10–12], respectively, into the concrete mixture. The cementitious properties of these wastes rely on their specific surface area and the pozzolanic behavior of their mineral composition. On a global scale, it is estimated that the yearly production of FA falls within the range of 0.75 to 1 billion tons [13]. Similarly, the production of GGBS typically ranges from 300–540 kg per ton, or rough iron used for mineral feed, with an iron content of 60–65%. In steel production, around 150–200 kg of GGBS are produced per ton of liquid steel. As developing nations have a growing demand for affordable energy, it is expected that this production volume will increase in the future[14]. Therefore, the widespread use of these wastes can be accomplished through their application in civil engineering [15,16].

As stated above, concrete has high compressive strength but low tensile strength[17–19]. Therefore, in order to examine the impact of fibers in conjunction with GGBS and FA, the researchers chose to incorporate polypropylene fibers (0–2.5% of the cement's weight) as an additive during the concrete preparation process[20]. It serves as an auxiliary material for reinforcing concrete. Incorporating fibers into concrete can prevent the development of shrinkage cracks and improve its mechanical characteristics[21–23]. Alhozaimy et al.[24] conducted a comprehensive and empirical study on the effects of small quantities of grouped fibrillated polypropylene filaments on the compressive and flexural strength and durability, as well as the impact of polypropylene fiber-reinforced concrete materials. The researchers demonstrated that the polypropylene filaments do not have any detrimental impact on the compressive or flexural characteristics. However, the filaments exhibited an increase in both flexural strength and impact resistance upon examination. Positive correlations were also identified between fibers and pozzolans. Qiana et al. [25] have investigated the improvement of fly debris, fiber size, and content in a composite material made of equal parts polypropylene and steel fibers mixed with concrete. The amount of fiber used in the mixture was modest, but it still had a significant impact on the overall mechanical properties of the material. The researchers discovered that the use of steel strands of different sizes resulted in varying mechanical properties, albeit to varying extents. Furthermore, it was observed that the choice of a tiny fiber type had an impact on the compressive strength, whereas the flexural strength was slightly affected. The presence of a large fiber type leads to opposite mechanical effects, which are further intensified by increasing the aspect ratio. Sivakumar et al. [26]evaluated the mechanical characteristics of several solid structures reinforced with fibers, including steel strands alone and combinations of steel with non-metallic filaments such as glass, polyester, and polypropylene. The filaments were maintained at a fixed absolute dosage of 0.5%. Based on the results, the researchers found that only the polypropylene fiber blend (containing 0.12% polypropylene filaments) outperformed the mono-steel fiber concrete in all aspects. It was observed that the flexural strength decreased as the amount of non-metallic strands increased.

1.1. Research significance and objective

The present investigation aims to minimize the quantity of OPC utilized in concrete production. The utilization of by-products not only mitigates the need for waste removal and storage but also mitigates the consequential environmental impacts and promotes sustainability[27]. The primary objective of the present study is to develop environmentally friendly concrete by utilizing industrial byproducts such as GGBS and FA. There is a lack of research on the utilization of MSF in binary blended concrete, specifically in combination with GGBS and FA. Therefore, the objective of the present study is to examine the physical and mechanical characteristics of binary concrete through the incorporation of MSF. This study aims to determine concrete physical and mechanical characteristics when OPC is partially substituted with GGBS at 20%, 25%, 30%, 35%,40%and with constant 20% FA. In addition, several volume fractions of MSF (0.5%, 1%, 1.5%and 2%) were incorporated into the concrete. The findings have been compared with standard concrete of M40 grade.

2. MATERIALS

2.1. Ordinary portland cement (OPC)

OPC 53 grade (IS: 269-2015) [28,29]. with a specific gravity of 3.14 was used in this investigation. The initial setting time of the OPC was 165 minutes, whereas the final setting time was 220 minutes. The Blain's specific surface area was measured to be 295 m^2/kg, and the soundness was 0.6 mm.

2.2. Ground-granulated blast furnace slag (GGBS) and fly ash (FA)

GGBS (IS 16714:2018) [30]and FA (IS 3812: 2013) [31] with a specific gravity of 2.86 and 2.17, respectively. The Blains specific surface area of GGBS was 388 m^2/kg was used in this work. The study utilized JSW brand GGBS and Ramagundam thermal power plant-based FA. Table 1 displays the chemical makeup of cement, GGBS, and FA. Fig. 1 displays SEM pictures showing that the FA particles mostly have a spherical shape, but the GGBS particles have more irregular crystals.

Table 1: Chemical composition of OPC, GGBS and FA

Constituent (wt.%)	OPC	GGBFS	FA
SiO_2	23.4	37.73	60.2
CaO	60.76	37.34	15.98
Al_2O_3	5.01	14.42	22.3
MgO	3.95	8.71	1.15
Fe_2O_3	4.46	1.8	0.17
SO_3	2.42	-	0.2

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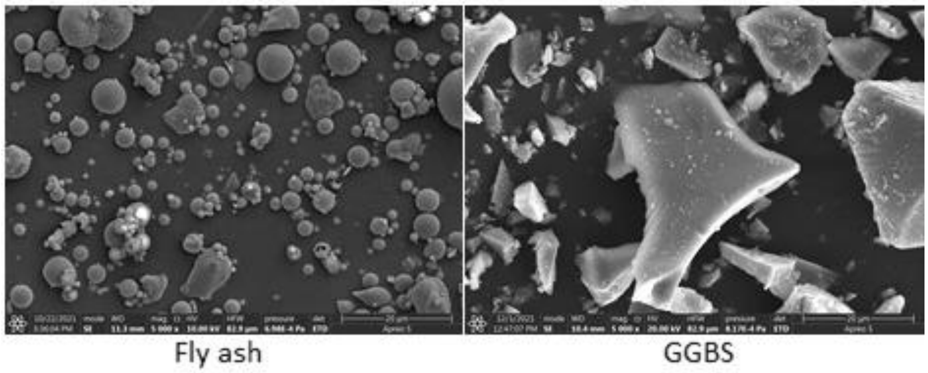

Fig.1: SEM pictures of FA and GGBS

2.3. Aggregates

Crushed stone aggregate with a maximum diameter of 20mm, a specific gravity of 2.64, a bulk density of 1.68 kg/litre, and a water absorption of 0.26% was utilized. As per the specifications of IS 383-2016[32], Zone-II river sand was utilized as a fine aggregate, possessing a specific gravity of 2.58 and a bulk density of 1.82 kg/liter.

2.4. Superplasticizer

The superplasticizer used in this study was Master Glenium Sky 8609 (IS 9103)[33], which was procured from M/s. Master Builders Solutions India Pvt. Ltd.

2.5. Macro synthetic fibers (MSF)

The MSF are designed to meet the specifications of ASTM C1116 Type III, ensuring their outstanding performance. Table 2 depicts the properties of MSF.

Table 2: Properties of MSF

Properties	Value
Density	0.910 g/cm^3
Diameter	0.8-1.8 mm
Length	45-50 mm
Tensile strength	>500 Mpa
Modulus of Elasticity	>/= 7000 Mpa
Aspect Ratio	36

3. EXPERIMENT METHODOLOGY

The concrete mix design was formulated as per IS 10262-2019[34]. The mix design maintains a constant binder content of 450 kg/m^3 and a water-binder ratio of 0.36. The volume of aggregates for design concrete was obtained by assuming that 1.5% of entrapped air is present in the fresh concrete. The aggregate volume per cubic meter of concrete determines the weight of the aggregates. For this study, different combinations were devised to assess the compressive strength, split tensile strength, and flexural strength of concrete, both with and without fibers. Table 3 displays the proportions of the concrete mixture and the designations of the mixture.

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The specimens were cured under water at 27 ± 2 °C until the appropriate age was obtained after casting. Standard code provisions were then used to evaluate concrete specimen characteristics at 7 and 28 days. Compressive strength was tested on 150mm concrete cubes in a 300-ton compression testing machine at 14 N/mm^2/minute until failure, according to IS: 516[35]. A 150 mm cube specimen was placed between the compression testing machine's platens and loaded at 1.2–2.4 N/mm2/minute until failure for tensile strength, as described in IS: 516 [35]. A 100 mm X 100 mm X 500 mm prism was placed on a 40-ton Universal Testing Machine (UTM) to assess flexural strength. The specimen was then gradually loaded with four points, as indicated in IS: 516 and IS: 17161[36,37].

4. RESULTS AND DISCUSSION

4.1. Workability

Slump cone test results for various MSF-reinforced binary concrete mixes are shown in Fig. 2. As the MSF content increases, the slump values gradually decrease. The slump values are higher for the conventional mix than for all other samples. Even though the slump values decrease due to adding MSF to concrete mixes, all samples are in an excellent workable stage per IS standards. It is clear from Fig. 2 that SP5 shows a higher slump of 125mm and SP29 shows a lower slump of 45mm. The results show no balling effect of MSF in binary concrete, and fibres are dispersed uniformly. An increase in the percentage of MSF content decreases concrete workability due to increased MSF stiffness compared to the reference mix.

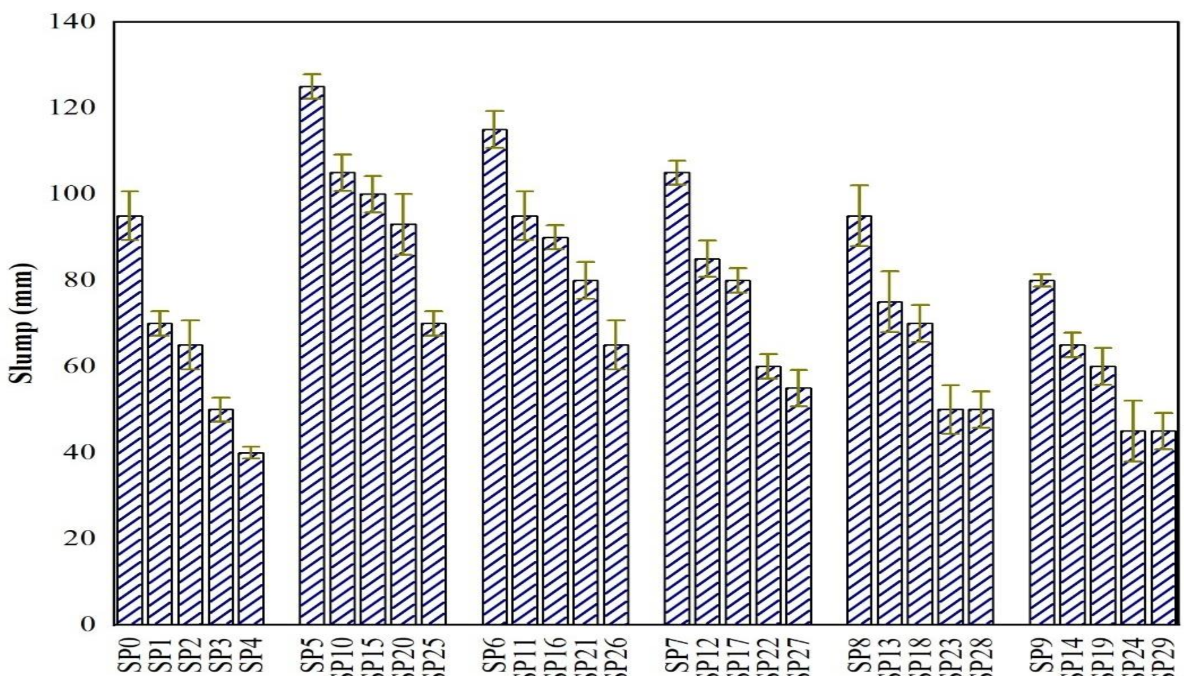

Fig.2: Workability of MSF-reinforced binary concrete mixes

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4.2. Compressive Strength

The results of the compressive strength of MSF-reinforced binary concrete are presented in Fig. 3. As the age of concrete increases, the compressive strength also increases due to continuous hydration. The addition of MSF resulted in anslight enhancement of the compressive strength of the binary concrete. The compressive strength of SP22 is observed to be higher than that of other samples at all ages. The strength of mix SP22 improved by 9.84% and 5.8%, respectively, compared to mix SP0 at 7 and 28 days. The improvement in the strength of the binary concrete was more pronounced after 28 days of curing. The continuous hydration process led to stronger bonding between the MSF and supplementary cementitious materials (i.e., GGBS and FA), achieving higher strength. As MSF is used, the bonding between the MSF and supplemental cementitious materials is powerful, contributing to strength improvement. MSF enhanced the OPC matrix's structural integrity, delaying the cracks' beginning, growth, and spread. This significantly increased post-cracking load resistance and improved compressive strength [18].

4.3. Split tensile strength

The findings of the splitting tensile strength of MSF-reinforced binary concrete are presented in Fig. 4. The split tensile strength increased with the incorporation of MSF into the binary concrete, improving tensile strength. The split tensile strength of SP22 is observed to be higher than that of SP0 at 7 and 28 days, respectively. At 7 days, the tensile strength of mix SP22 was higher by 65.18% compared to mix SP0. Similarly, at 28 days, the tensile strength of mix SP22 was superior by 61.31% compared to SP0. The increase in split tensile strength with the addition of MSF to the binary concrete is due to the high tensile strength of the fibre, which invariably increases the tensile strength of all the samples. The MSF also made the concrete more flexible and resistant to load after cracking by stopping cracks from starting, growing, and spreading when it was under tensile load, which increased its tensile strength[21,24].

4.4. Flexural strength

The results of the MSF-reinforced binary concrete are presented in Fig. 5. When the compressive and tensile strengths increased, the binary concrete's flexural strength rose when the MSF content increased on each of the corresponding days. Compared to the SP0, the flexural strength of mixed SP22 mixes was higher by 20.65% at 7 days and 26.22% at 28 days, respectively. The addition of MSF is mostly responsible for the increase in flexural strength. Additionally, due to its high tensile loads, MSF significantly improved its bending resistance when added to binary concrete. Furthermore, due to its crack bridging through strong bonding, MSF increases the resistance to post-cracking failure and delays the failure of the concrete when it is subjected to bending loads by transferring and redistributing stresses throughout the matrix [16,26].

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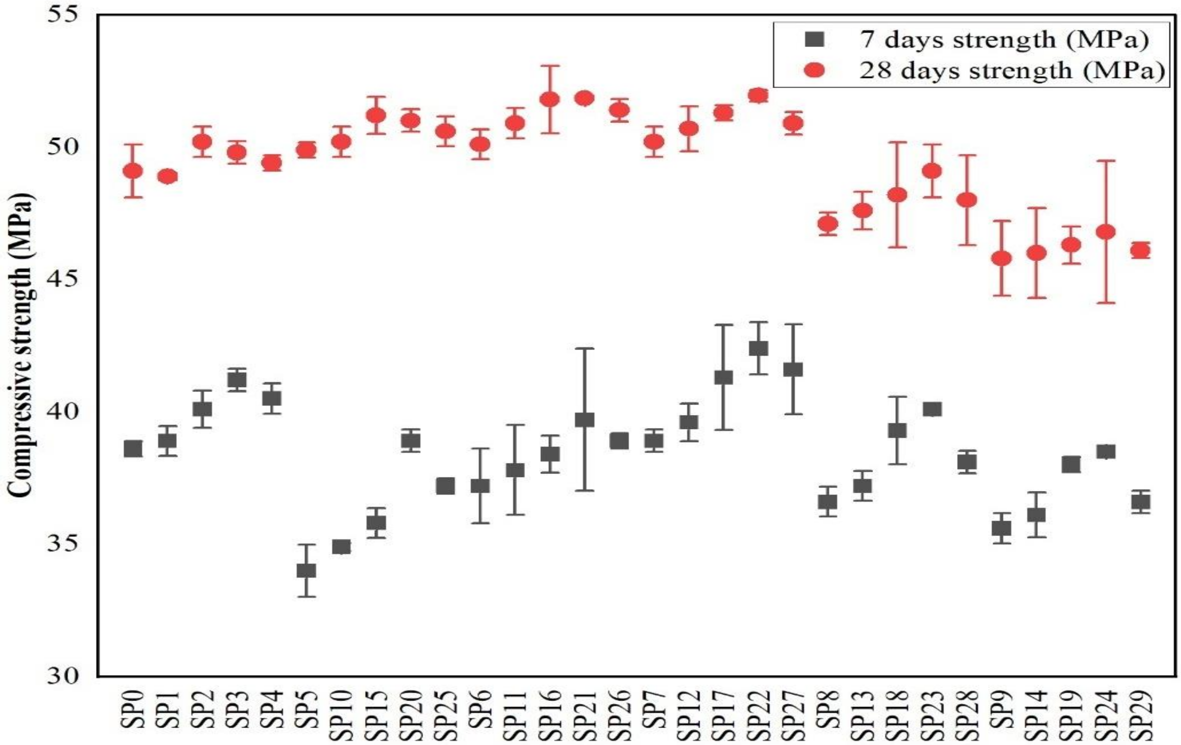

Fig.3: Compressive strength of MSF-reinforced binary concrete mixes

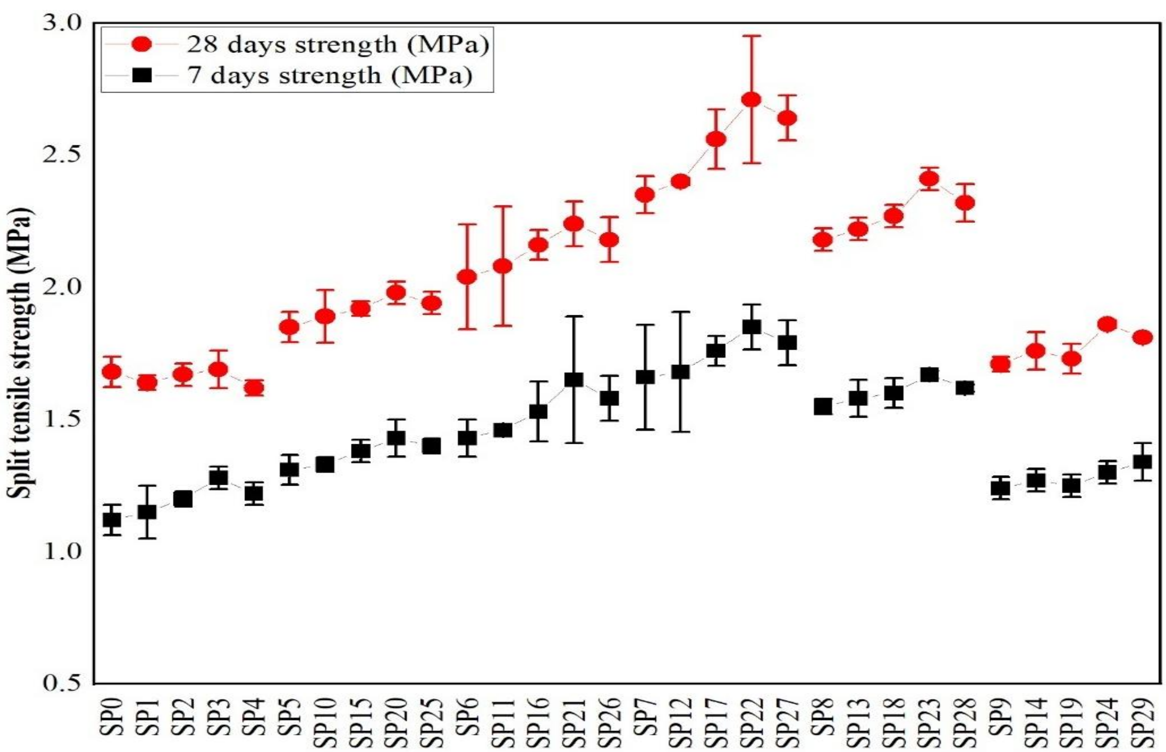

Fig.4: Split tensile strength of MSF-reinforced binary concrete mixes

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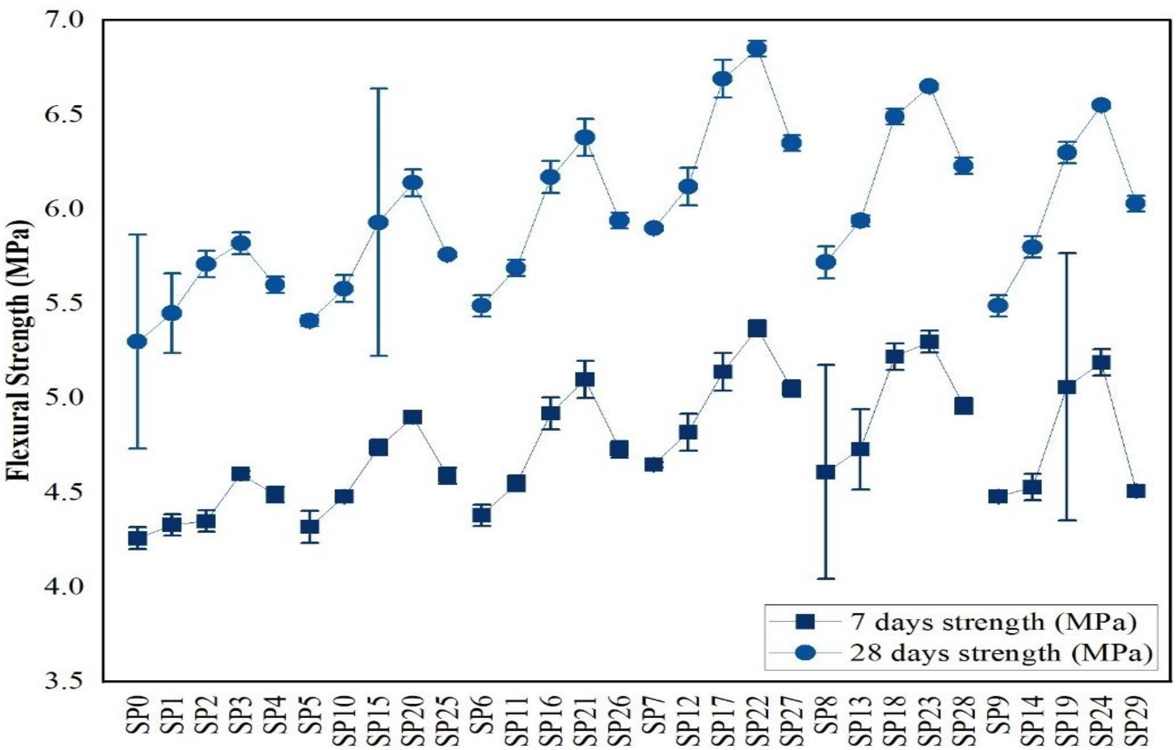

Fig.5: Flexural strength of MSF-reinforced binary concrete mixes

Table 3: Mix Proportions (kg/m^3)

Mix ID	W/C	Cement (kg/m^3)	Macro synthetic fibres (MSF) %	Cementitious material (kg/m^3)		Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	Admixture (kg/m^3)
				GGBS	FA			
SP0	0.36	450	0.0	0.0	0.0	758.40	1026.80	0.90
SP1	0.36	450	0.5	0.0	0.0	758.40	1026.80	0.90
SP2	0.36	450	1.0	0.0	0.0	758.40	1026.80	0.90
SP3	0.36	450	1.5	0.0	0.0	758.40	1026.80	0.90
SP4	0.36	450	2.0	0.0	0.0	758.40	1026.80	0.90
SP5	0.36	270	0.0	90	90	758.40	1026.80	0.90
SP6	0.36	248	0.0	112	90	758.40	1026.80	0.90
SP7	0.36	225	0.0	135	90	758.40	1026.80	0.90
SP8	0.36	203	0.0	157	90	758.40	1026.80	0.90
SP9	0.36	180	0.0	180	90	758.40	1026.80	0.90
SP10	0.36	270	0.5	90	90	758.40	1026.80	0.90
SP11	0.36	248	0.5	112	90	758.40	1026.80	0.90
SP12	0.36	225	0.5	135	90	758.40	1026.80	0.90
SP13	0.36	203	0.5	157	90	758.40	1026.80	0.90
SP14	0.36	180	0.5	180	90	758.40	1026.80	0.90
SP15	0.36	270	1.0	90	90	758.40	1026.80	0.90
SP16	0.36	248	1.0	112	90	758.40	1026.80	0.90
SP17	0.36	225	1.0	135	90	758.40	1026.80	0.90
SP18	0.36	203	1.0	157	90	758.40	1026.80	0.90

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SP19	0.36	180	1.0	180	90	758.40	1026.80	0.90
SP20	0.36	270	1.5	90	90	758.40	1026.80	0.90
SP21	0.36	248	1.5	112	90	758.40	1026.80	0.90
SP22	0.36	225	1.5	135	90	758.40	1026.80	0.90
SP23	0.36	203	1.5	157	90	758.40	1026.80	0.90
SP24	0.36	180	1.5	180	90	758.40	1026.80	0.90
SP25	0.36	270	2.0	90	90	758.40	1026.80	0.90
SP26	0.36	248	2.0	112	90	758.40	1026.80	0.90
SP27	0.36	225	2.0	135	90	758.40	1026.80	0.90
SP28	0.36	203	2.0	157	90	758.40	1026.80	0.90
SP29	0.36	180	2.0	180	90	758.40	1026.80	0.90

5. CONCLUSIONS

In this study, the impact of MSF in various proportions (0%, 0.5%, 1%, 1.5%, and 2%) on the use of GGBS in varying percentages (20%, 25%, 30%, 35%, and 40%) with 20% FA is attempted.

- This research shows the workability of MSF-reinforced binary concrete compared to reference mix SP0. Similarly, the same workability improvement trend is noticed for the SP5 sample with a slump of 125mm prepared with 20% FA and 20% GGBS. It indicates that using ultrafine particles of FA and GGBS improves the fluidity properties of MSF-reinforced binary concrete and lessens the internal friction between supplementary cementitious materials. Similarly, using a higher amount of MSF decreases the workability of concrete.
- Compressive strength results indicate that GGBS can be used up to 30% along with FA (20%) without affecting the strength characteristics of MSF-reinforced binary concrete. After that, a marginal decrease in compressive strength is noticed for the mixes using 2% MSF. Cao and Al_2O_3 in GGBS and FA waste powder, respectively, react with cement constituents and form CSH gel formation, thus improving concrete properties over time. Similarly, using MSF (1.5% by volume) in MSF-reinforced binary concrete reduces the voids, arrests the micro-crack formation, and makes mixes less porous. Thus, improvement in strength is noticed until mixed (1.5 % MSF, 20% FA and 30% GGBS), with a 28-day strength of more than 51 Mpa, justifying MSF.
- A tensile strength improvement of 2.71 MPa is noticed for sample SP22 (1.5% MSF, 20% FA and 30% GGBS) compared to a strength of 1.68 MPa for SP0. However, using 2% MSF affects the strength. This improvement in strength established the role of MSF, resulting in a dense concrete microstructure and reduced voids and crack formation.
- Like compressive and tensile strength, a comparable trend was observed, with a flexural strength improvement of 6.85 MPa for sample SP22 (1.5% MSF, 20% FA, and 30% GGBS) compared to a strength of 5.30 MPa for SP0. However, using 2% MSF affects the strength. MSF usage slows the growth of microcracks both before and after peak stress, and the iron concentration of GGBS increases the density of the concrete.

5.1. Limitations of the study and scope for future work

The study illustrates using MSF and partially replacing OPC with GGBS and FA without compromising the strength qualities, which is in keeping with the goal and scope of this research. This study examined the effects of fibres in GGBS and FA on the mechanical and fresh characteristics of M40-grade concrete. Other concrete grades and other additive and superplasticizer combinations were not covered.

While these experiments aid in the development of new green concrete by academics and practitioners, much more work has to be done to understand the usage of MSF in different percentages in different grades of concrete. Similarly, by employing mathematical or optimization or modelling, the researchers may expand their study to ascertain the best use of GGBS, FA, and MSF. The authors hope this study will pave the way for further investigations and applications that benefit practitioners and scholars.

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