

<https://doi.org/10.48047/AFJBS.6.14.2024.8779-8789>



African Journal of Biological Sciences

Journal homepage: <http://www.afjbs.com>



Research Paper

Open Access

EXPERIMENTAL INVESTIGATIONS ON SELF COMPACTING CONCRETE WITH SLAG POWDER

Dr E. V. Raghava Rao¹, Tangudu Manoj², Dr. Talakola Lakshmi Ramadasu³,
Dr.M.Samuel Thanaraj⁴, Jagadeesh Bommisetty⁵, Kamlesh Vasantrao Madurwar⁶

¹Professor & HOD, Department of Civil Engineering, Kalinga University, Kotni,Naya Raipur-492101, Chhattisgarh, India.

²Assistant Professor, Department of Civil Engineering, CVR College of Engineering, Hyderabad, Telangana, India.

³Associate Professor, School of Civil Engineering, PNG University of Technology, LAE-411, Morabe Province, Papua Newgunia.

⁴Assistant Professor (SG), Department of Civil Engineering, Nehru Institute of Technology, Jawahar Gardens, Kaliapuram, Coimbatore 641025, Tamil Nadu, India.

⁵Assistant Professor, Department of Civil Engineering, CVR College of Engineering, Hyderabad, Telangana, India.

⁶Assistant Professor, Department of Civil Engineering, Priyadarshini Bhagwati College of Engineering, Harpur Nagar, Nagpur-440009, Maharashtra, India.

Volume 6, Issue 14, Aug 2024

Received: 15 June 2024

Accepted: 25 July 2024

Published: 15 Aug 2024

doi: [10.48047/AFJBS.6.14.2024.8779-8789](https://doi.org/10.48047/AFJBS.6.14.2024.8779-8789)

Abstract: This study examines the impacts of somewhat subbing concrete with fly debris and slag powder, alongside consolidating 6% miniature steel strands, on the functionality and mechanical properties of self-compacting concrete. Through thorough trial and error, we evaluated usefulness qualities like ability to fill, union, and porousness, as well as mechanical characteristics like compressive strength, pivotal compressive strength, parting elasticity, and flexural strength. Workability is reduced but cohesiveness is increased when micro-steel fibers are mixed with fly ash and slag powder, according to the findings. Fly debris predominantly improves tractable properties, while slag powder helps compressive and flexural properties. Fibers made of micro-steel significantly enhance mechanical performance as a whole.

Keywords: fly ash; slag powder; micro-steel fibre; self-compacting concrete; workability; mechanical properties

1. Introduction

Self-compacting concrete (SCC) accomplishes uniform compaction through gravity, disposing of the requirement for vibration, and displays outstanding flowability, penetrability, and protection from isolation. SCC is ideal for projects with complex steel reinforcement and limited pouring spaces due to

its superior performance. Nonetheless, the significant measure of cement required increments creation costs, and SCC's intrinsic fragility prompts usefulness misfortune after breaking. Steel fibers, in particular, can bridge cracks and increase the brittleness of concrete, thereby increasing structural ductility and crack resistance. However, steel fibers with a large diameter restrict dosage, decrease flowability, increase weak spots, and impact overall performance. Steel fibers that are too many can also reduce the matrix, making the fibers more likely to break. Concentrates on show that utilizing a solitary gel material cutoff points steel fiber measurement, while high concrete substance raises concerns like high hydration intensity, shrinkage, and cost. Steel fiber-reinforced SCC (SFSCC) alternative cementitious materials have been investigated by researchers. Fly debris expansion expanded droop stream to 67 cm, refined pores, worked on interfacial holding, and improved mechanical properties, however its bigger molecule size can obstruct working properties. Due to its high reactivity and friction, silica fume reduced slump flow to 55 cm while increasing compressive strength. Volcanic pumice powder diminished droop stream to 49 cm because of expanded consistency however essentially worked on mechanical properties. These investigations feature that various admixtures can change substantial properties; however, a solitary material expansion can't address different execution necessities.

Specialists have perceived the restrictions of utilizing a solitary material and have tried steel fiber-built up self-compacting concrete (SFSCC) with different concrete substitutes. Iman Ferdosian and Jingjun Li discovered that the combination of fly ash and silica fume increased mechanical properties but not slump flow to the desired level. A slump flow of 66 cm was achieved in other studies employing silica nanoparticles, fly ash, and slag powder, including those by Thamer Alomayri, Anl Nis, and Mehmet Eren Gülsan. These nanoparticles further developed usefulness and effect obstruction however adversely impacted compressive strength and versatile modulus. G did more research. Laxmi and Abhay V. Nakum utilized just fly debris and slag powder, bringing about droop stream tests going from 65 cm to 75 cm, demonstrating amazing usefulness. Fly debris further developed blend execution and usefulness, while slag powder decreased hydration heat and inside breaking. These materials preserved the performance of the concrete due to the steel fibers' resistance to cracking. These examinations recommend that utilizing fly debris and slag powder together is the best methodology, upgrading functionality, strength, and sturdiness in SFSCC.

In conclusion, steel fiber self-compacting concrete (SFSCC) can improve its workability and mechanical properties by replacing cement with fly ash and slag powder. Notwithstanding, expanding upon the discoveries of a past period of this review, which uncovered almost deficient flowability, we plan to research the effect of elective gel materials on the presentation. In addition, little research has been done on the efficacy of SFSCC with dual admixtures of slag powder and fly ash. In order to investigate the workability and mechanical properties of the self-compacting concrete used in this study, the dual admixtures of fly ash and slag powder were chosen to replace cement. Micro-steel fibers of a smaller size were also incorporated into the concrete. Furthermore, a reviewed volume part of miniature steel filaments (0%, 1.5%, 3%, 5%, 6%) was utilized to methodically study and dissect the exhibition of high-satisfied miniature steel fiber self-compacting concrete blended in with fly debris and slag powder. The results of this study can be used to improve engineering applications and the design of concrete mixtures.

2. Materials and Mix Proportion

2.1. Gel Material

The gel materials utilized in this study included Portland concrete, fly debris, and slag powder. The standard Portland cement had a specific surface area of 346 m²/kg and a density of 3.08 g/cm³. Fly debris with a particular surface area of 480 m²/kg and slag powder with a particular surface area of 412 m²/kg were consolidated as elective materials to fill in for Portland concrete in the substantial combination.

The density of the fly ash was determined to be 2.55 g/cm³, and its moisture content was found to be between 0.85% and 1%. At, the density of slag powder of grade S95 was measured. 2.9 g/cm³, which is lower than the thickness of concrete.

2.2. Steel Fiber

The milling and copper coating of the steel fibers used in this study made it easier for them to be evenly distributed throughout the concrete mixture. With a strength of 2869 MPa, these fibers demonstrated exceptional dispersibility, strength, and stability. Their little size considered a high measurement in self-combining concrete.

2.3. Aggregate

The fine total used in this exploration comprised of common medium sand with a fineness modulus of 2.6 and an earth content of 3.3%. The limestone that was crushed was the source of the coarse aggregate, which contained 9.7% needle-like particles. The coarse aggregates of 5–10 mm and 10–16 mm was blended using a mass-to-weight ratio of 1:1.

2.4. Additives

The water minimizer utilized in this study was a standard polycarboxylic corrosive highperformance water minimizer, with a strong substance of 17.76% and a water decrease pace of 30%. The BASF F10 polycarboxylic acid powder served as the raw material for the preparation of the water reducer. A completely non-segregated gypsum mixture can be made by adding a water reducing agent. F10 can decrease blending, immediately cement, increment the smoothness of cement, and further develop droop. The dosage of 0.18 percent was chosen after numerous tests to determine the cementitious material's quality.

2.5. Mix Proportion

In this examination, a mix of miniature steel strands, fly debris, and slag powder as mixed strengthening materials was utilized. The total dosage of blended materials, which included a mixture of the two mineral admixtures, was set at 30% in a control group. Slag powder and fly ash weighed in at 20% + 10%, 15% + 15%, and 10% + 20%, respectively. The measurements of miniature steel strands went from 0% to 6%, with gradually chose volume proportions of 0%, 1.5%, 3%, 5%, and 6%. The goal was to examine the varieties in usefulness and mechanical properties of SCC containing steel filaments under various extents of fly debris and slag powder.

3. Testing Procedure

3.1. Workability Test

Fundamental aspects of SCC flowability include fluidity, passing ability, and resistance to segregation. In this review, the ability to fill is surveyed through droop stream tests, cohesiveness is

assessed by means of V-pipe tests, and passing not entirely set in stone by L-box tests. The guidelines outlined in the Chinese standard for self-compacting concrete, JGJ/T283-2012, are followed in these procedures.

3.1.1. Slump Flow Test

The slump flow test is carried out on a horizontal surface. First, the slump cone is filled with the new concrete mixture, and then it is raised quickly and steadily in a vertical direction. The height is measured with a ruler when the flow ceases, and the concrete mixture's flow behaviour is observed until the slump flow stabilizes.

3.1.2. V-Funnel Tests

From the funnel's top, the concrete mixture is poured into the V-shaped funnel. In the wake of permitting the blend to stand undisturbed for 1 min, the valve at the lower part of the channel is opened. A stopwatch is used to precisely measure the concrete's flow time, which is the period of time from the beginning of the flow until the discharge is complete. All the while, any event of blockage during the stream cycle is noticed and recorded.

3.1.3. L-Box Tests

The pre-arranged substantial blend is filled the upward segment of the case. The vertical and horizontal switch panels are raised to begin the concrete flow after allowing it to settle for one minute without being disturbed. From the beginning of the concrete flow until it reaches the bottom of the horizontal section, time is recorded. In particular, separate records are kept of the time it took for the concrete to flow to the 200 mm and 400 mm marks in the horizontal section. After the stream stops, the levels at the front and back finishes of the flat segment are estimated to evaluate any potential level contrast and decide the levelness of the substantial stream.

3.2. Mechanical Performance Test

The mechanical presentation was assessed through tests including compressive strength of cubic examples, hub compressive strength tests, dividing malleable tests, and flexural strength tests. A sum of 15 different blend proportions were tried. The compressive strength, pivotal compressive strength, and parting elasticity were estimated utilizing a general testing machine, while the flexural strength of shaft examples was estimated at three focuses utilizing a flexural strength testing machine.

3.2.1. Cube Compression Test

Mechanical execution tests were directed as per the Chinese standard GB/T 50081-2019, including solid shape compressive strength tests, crystal hub compressive strength tests, dividing elastic tests, and flexural strength tests. There was a total of fifteen different mix proportions tested. For the compressive strength tests, both 3D shapes and crystal examples of various sizes were tried. This is due to the fact that the stress state experienced by structural elements like columns and walls in concrete structures may differ from that of cube specimens. As a result, cube specimens can accurately portray the concrete's overall compressive performance while prism specimens can provide data on compressive strength that is more representative of actual conditions. A comprehensive evaluation of concrete's compressive performance is made possible by testing both the cube compressive strength and the prism axial compressive strength simultaneously.

3.2.2. Axial Compressive Test

The hub compressive strength of cement is like the compressive strength of solid shapes and is a key exhibition sign of cement's compressive strength. However, prismatic specimens are used in place of square cubes for the axial compressive strength test. The components of the test examples are 100 mm $\times$ 100 mm $\times$ 300 mm. Axial compressive strength testing is similar to cube compressive strength testing. As per the working guidelines of the general testing machine, the crystal is situated in the upper and lower platens, and afterward stacked until the example falls flat.

3.2.3. Splitting Tensile Strength Test

With minimal tensile stress and no excessive deformation prior to failure, the entire internal structure of traditional SCC without steel fibers exhibits brittle behavior. Conversely, SCC with steel strands doesn't go through unexpected burst under pliable powers yet rather flops progressively and all the more totally. The parting elasticity, mirroring the substantial's capacity to oppose breaking, really shows the meaning of high-volume miniature steel fiber SCC. In this examination, cubic examples (100 mm $\times$ 100 mm $\times$ 100 mm) were utilized to concentrate on the parting elasticity of the substantial. Steel plates and wooden spacer layers were put at the base and top of the examples. The specimen was separated from the steel plates by wooden spacers, which reduced the area of contact and allowed for tensile strength testing. The steel plates made contact with the upper and lower plates of the testing machine. The pressure caused the wooden spacers, which were only used once to avoid having a significant impact on the tensile strength values, to deform and become damaged.

3.2.4. Bending Resistance Test

The flexural strength of cement is concentrated on utilizing shape pillar examples with aspects of 100 mm $\times$ 100 mm $\times$ 400 mm. The experiment makes use of a flexural strength testing machine at Chongqing Jiao tong University's Road Engineering Laboratory. The concrete specimens and the apparatus for testing flexural strength. The three-point twisting technique is utilized to test the examples, with two stacking focuses put on the upper piece of the example. The testing is carried out by directing the machine until the specimen fails, at which point the test is stopped.

4. Results and Discussion

4.1. Fresh Properties

The functionality testing results for five different blend extents are shown in Table 1. The ability to fill voids, their cohesion, and their permeability will each be examined in its own section.

Table 1. Workability results.

Number	SF (mm)	VF (s)	L-Box (s)	Δ L-Box (mm)
A-0	670	40	21	15
B-0	685	35	18	10
C-0	695	32	13	8
A-1.5	650	67	27	32
B-1.5	665	62	27	38
C-1.5	680	55	21	27
A-3	620	116	48	49

B-3	640	140	46	45
C-3	660	134	37	39
A-5	605	154	54	74
B-5	610	165	59	60
C-5	620	152	58	65
A-6	590	210	80	90
B-6	595	203	75	85
C-6	610	198	70	82

4.1.1. Filling Ability

The slump flow test looks at a concrete mixture's ability to flow freely, which shows how workable and fillable it is. When the steel fiber dosage is 6 percent, the experimental results show that the mixture has a minimum flow diameter of 590 mm, which is within the JGJ/T283-2012 minimum standard limit of 550 mm. The variety in droop stream with expanding miniature steel fiber content from 0% to 6% for the three mixes of fly debris and slag powder as the steel fiber content expanded, the downturn stream of various extents of mixed combinations showed a diminishing pattern. When compared to the other two mix proportions, slump flow was higher in the mixture with a slag powder content of 20%. When fly ash and slag powder were mixed equally, the overall flowability was lower, while the mixture with more fly ash had the lowest flowability. This variety can be ascribed to the impact of slag powder content on flowability. When the percentage of slag powder was 20%, the highest slump flow value was 695 mm; however, when the percentage of fly ash was 20%, the slump flow was only 670 mm. Mixtures with a higher proportion of slag powder exhibited better flowability than other mix proportions throughout the entire trend, with a difference of approximately 4% between the highest and lowest values. This peculiarity shows that with an expansion in slag powder content, the flowability of the combination improves somewhat.

4.1.2. Cohesiveness

The flow time through a V-shaped funnel was used to assess the concrete mixture's cohesion performance. While an excessively long flow time indicates poor mixture flowability, a longer flow time indicates superior cohesion performance. Overall, the group with the highest concentration of fly ash had a longer flow time than the group with the highest concentration of slag powder. The group with a higher proportion of slag powder had the shortest flow time—32 seconds—when the steel fiber content was zero, whereas the group with a higher proportion of fly ash had the longest flow time—40 seconds—when the steel fiber content was zero. This suggests that the group with a higher proportion of slag powder performed better in terms of cohesion when steel fibers were not present. When the steel fiber content was 6%, the flow time for the group with the most fly ash was 210 s, the group with the same amount of fly ash and slag powder was 203 s, and the group with less fly ash was 198 s. All three mix proportions of blended materials showed significantly improved cohesion performance as the steel fiber content increased, and the mixture's overall integrity improved as it flowed out of the funnel. A higher proportion of fly ash resulted in lower flowability for slag powder and fly ash, indicating improved cohesion performance of the mixture.

4.1.3. Passing Ability

Under various additive proportions, the time it takes for the mixtures from each group to reach the bottom of the horizontal trough through the outlet was 21 s, 18 s, and 13 s, respectively, when the steel fiber content was zero. This is used to evaluate the permeability performance. The distinction between the three gatherings was not huge, yet the gathering with a higher slag powder content showed

somewhat better porousness execution. At the point when the steel fiber content was 6%, the ideal opportunity for the three blends to go through was 80 s, 75 s, and 70 s, individually, with the combination containing a higher fly debris content appearance marginally less fortunate porousness execution. When the mixtures were observed, it was discovered that as the amount of steel fibers increased, the speed at which the mixture passed through the steel rebar slowed significantly, which had a significant impact on the permeability performance. After the mixture stopped flowing, the height difference between the front and rear troughs was measured. A higher height difference indicates that the mixture's permeability performance is lower. Test results showed that when the steel fiber content was 0%, the level distinctions for the three mixed blend extents were 15 mm, 10 mm, and 8 mm, individually. There was little difference in permeability performance between the three proportions when the steel fiber content was 6%. The height differences for the various groups were 90 mm, 85 mm, and 82 mm, respectively. By looking at the porousness execution at various steel fiber contents, it was found that the expansion in steel fiber content extraordinarily impacted the capacity of the blend to go through complex rebar regions. The maximum amount of steel fibers that can be used in this experiment is now 6 percent.

4.2. Mechanical Properties

Various sizes of test examples were exposed to compressive strength tests, pivotal compressive strength tests, dividing tractable tests, and flexural strength tests. Three examples were taken for each test from each blend extent, and the number juggling normal of the experimental outcomes was taken as the last strength esteem. The outcomes of the analysis are as follows:

4.2.1. Cube Compressive Strength

The exploratory information results were plotted in Figure 1. The experimental outcomes show that when the steel fiber content is 0%, among the three blend extents, the most noteworthy compressive strength worth of 44.7 MPa is accomplished when the slag powder content is 20%, while the least compressive strength of 41.9 MPa is gotten when the fly debris content is 20%. The two are approximately 7 percent apart. It goes without saying that the strength of the concrete rises in proportion to the amount of slag powder present. The strength of the three groups of specimens significantly increases with the amount of steel fiber present. At the point when the steel fiber content is 6%, the blend in with a higher slag powder content accomplishes the most noteworthy compressive strength of 75.8 MPa, showing a critical improvement of 69.6%. With a 76.8% overall improvement, the mix has the greatest improvement. However, there is a small gap between the three at this point. By examining the reason, it can be seen that fly ash and slag powder have less of an effect on concrete when the fiber content is very high.

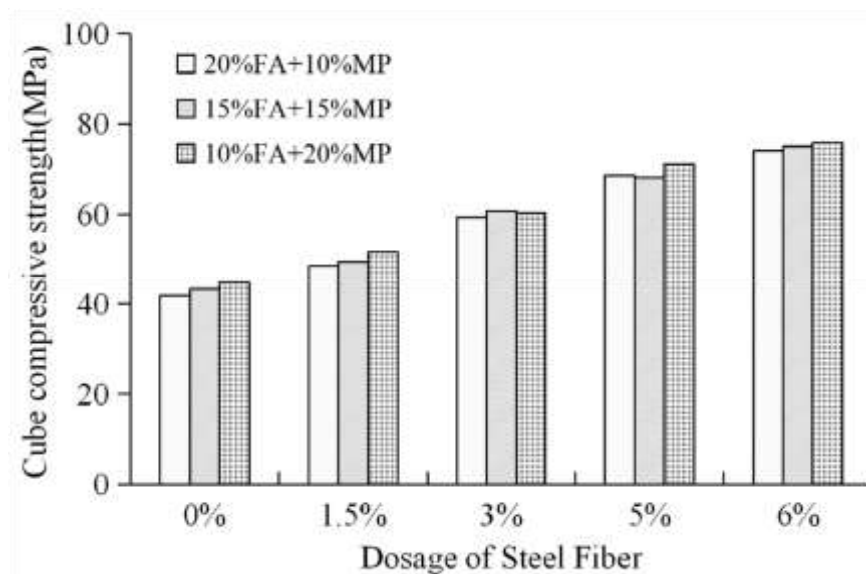


Figure 1. Cube compressive strength in different proportions.

4.2.2. Axial Compressive Strength

The exploratory data results were plotted in Figure 1. According to the results of the experiments, the three blend levels with 0% steel fiber have the highest compressive strength of 44.7 MPa when the slag powder content is 20%, while the lowest compressive strength of 41.9 MPa is achieved when the fly debris content is 20%. The two of them are only about 7% apart. It goes without saying that the amount of slag powder in the concrete increases its strength. The presence of steel fiber significantly increases the strength of the three groups of specimens. Exactly when the steel fiber content is 6%, the mix in with a higher slag powder content achieves the most important compressive strength of 75.8 MPa, showing a basic improvement of 69.6%. The mix has the greatest improvement, with an overall improvement of 76.8%. However, there is currently a small gap between the three. Examining the reason reveals that concrete with a high fiber content is less affected by fly ash and slag powder.

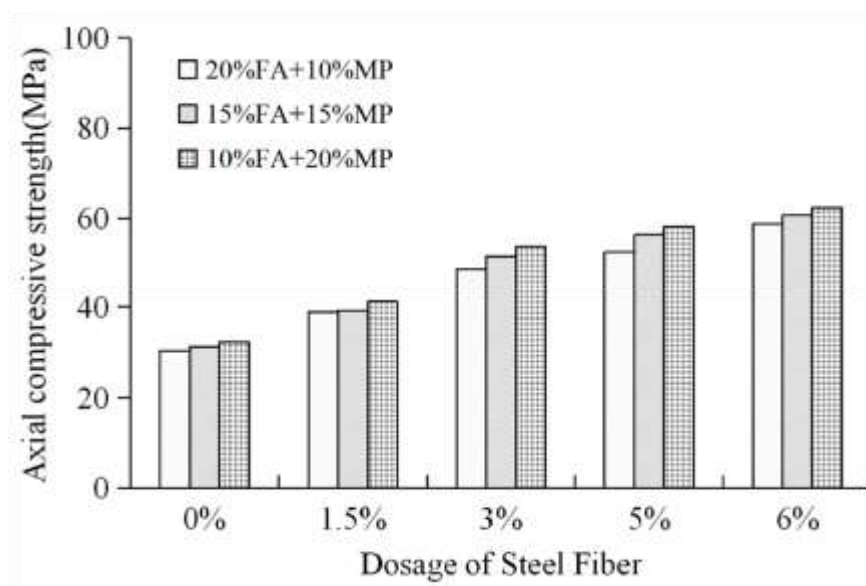


Figure 2. Axial compressive strength under different proportions.

4.2.3. Splitting Tensile Strength

As per the trial information in Figure 3, it tends to be seen that when the steel fiber content is 0%, the example with a higher fly debris content has the most noteworthy elasticity esteem, coming to 5.2 MPa. The group with the lowest tensile strength, with a value of 4.7 MPa, has a lower fly ash content. As the fly ash content decreases, so do the tensile strength values. 10% separates the maximum and minimum values.

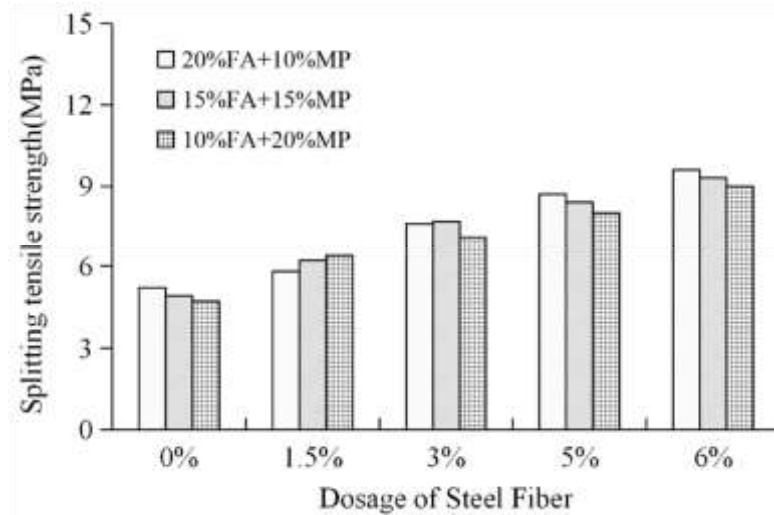


Figure 3. Splitting tensile strength under different proportions.

The tensile strength of each group increases linearly with the amount of steel fiber. The gathering with a steel fiber content expanding from 0% to 1.5% accomplishes the biggest improvement. The highest tensile strength is 9.6 MPa at a steel fiber content of 6%.

4.2.4. Flexural Strength

Figure 4 depicts the test results for the flexural strength of concrete. When the steel fiber content is zero, the specimen containing 20 percent slag powder has the highest flexural strength of 5.4 MPa, while the specimen containing 20 percent fly ash has the lowest strength, measuring 4.7 MPa. The distinction between the greatest and least qualities is 15%. It tends to be seen that when the aggregate sum of admixture is 30%, a higher slag powder content prompts a higher flexural strength.

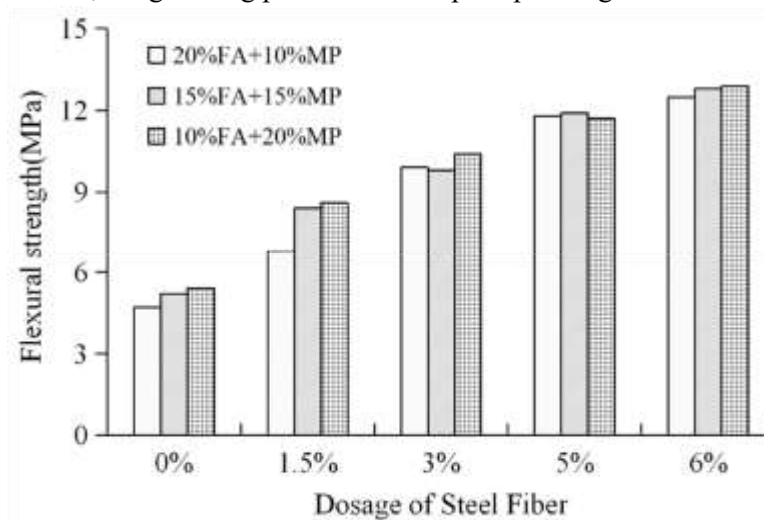


Figure 4 Flexural strength at different proportions.

The maximum increase in flexural strength is greater than with increasing steel fiber content. 100 percent for all gatherings. At the point when the steel fiber content arrives at 6%, the example with 20% fly debris content encounters the most elevated improvement, coming to 165.9%. The flexural strength value at this point is 12.5 MPa. The specimen with the highest flexural strength, 12.9 MPa, contains 20% slag powder. The disparity in flexural strength between the various proportions decreases as the content of steel fibers increases. It can be deduced that the effect on flexural strength is greater than that of admixtures at high steel fiber content.

5. Conclusions

SCC with varying amounts of fly ash and slag powder, a high micro steel fiber content, and workability and mechanical properties are the subjects of this investigation.

The main findings are:

- While adding more slag powder improves flowability, it weakens the material's cohesion. Higher steel fiber content decreases flowability and increments union. Flowability is significantly affected by admixtures at lower steel fiber contents, whereas steel fibers dominate at higher steel fiber contents.
- Higher steel fiber content improves mechanical execution. Fly ash boosts tensile strength and slag powder boosts compressive and flexural strengths at lower fiber contents. With more steel filaments, the admixtures' effect reduces.
- The review accomplishes a steel fiber measurement of up to 6%, contrasted with the run of the mill <2%. At 6% fiber content, the substantial shows significant upgrades in 28-day compressive strength (84.8%), hub compressive strength (93.9%), parting rigidity (116.3%), and flexural strength (165.9%) while keeping up with great self-compaction properties.
- When complete admixtures are $\leq 30\%$ with low steel fiber content, slag powder upgrades functionality yet can cause draining at high doses. Slag powder works on compressive and flexural qualities, while fly debris better works on rigidity. Fibers have a greater impact on workability and mechanical properties than admixtures at high steel fiber dosages. In a nutshell, combining fly ash and slag powder with micro steel fibers results in increased fiber dosage and improved concrete properties, paving the way for additional research.

References

1. Ramkumar, K.B.; PR, K.R.; Gunasekaran, K. Performance of hybrid steel fiber-reinforced self-compacting concrete RC beam under flexure. *Eng. Sci. Technol. Int. J.* **2023**, *42*, 101432.
2. Buratti, N.; Mazzotti, C.; Savoia, M. Post-cracking behaviour of steel and macro-synthetic fibre-reinforced concretes. *Constr. Build. Mater.* **2011**, *25*, 2713–2722.
3. Aslani, F.; Hamidi, F.; Valizadeh, A.; Dang, A.T. High-performance fibre-reinforced heavyweight self-compacting concrete: Analysis of fresh and mechanical properties. *Constr. Build. Mater.* **2020**, *232*, 117230.
4. Ortiz, J.A.; de la Fuente, A.; Mena Sebastia, F.; Segura, I.; Aguado, A. Steel-fibre-reinforced self-compacting concrete with 100% recycled mixed aggregates suitable for structural applications. *Constr. Build. Mater.* **2017**, *156*, 230–241.
5. Benedetty, C.A.; Krah, P.A.; Goes, C.M.W.; de Almeida, L.C.; Trautwein, L.M.; Silva, F.A. Effects of fiber content, inclination angle, and casting point on the fiber-matrix interaction of High-Strength Fiber-Reinforced Self Compacting Concrete. *Constr. Build. Mater.* **2023**, *398*, 132537.

6. Kaplan, G.; Bayraktar, O.Y.; Memis, S. Effect of high volume fly ash and micro-steel fiber on flexural toughness and durability properties in self-compacting lightweight mortar (SCLM). *Constr. Build. Mater.* **2021**, *307*, 124877.
7. Ferdosian, I.; Camões, A. Mechanical performance and post-cracking behavior of self-compacting steel-fiber reinforced ecoefficient ultra-high performance concrete. *Cem. Concr. Compos.* **2021**, *121*, 104050.
8. Laxmi, G.; Patil, S.; Hossiney, N.; Thejas, H.K. Effect of hooked end steel fibers on strength and durability properties of ambient cured geopolymer concrete. *Case Stud. Constr. Mater.* **2023**, *18*, e2122.
9. Fu, Q.; Bu, M.; Zhang, Z.; Xu, W.; Yuan, Q.; Niu, D. Hydration characteristics and microstructure of Alkali-Activated slag concrete: A review. *Engineering* **2023**, *20*, 162–179.
10. Ge, Z.; Wang, Y.; Sun, R.; Wu, X.; Guan, Y. Influence of ground waste clay brick on properties of fresh and hardened concrete. *Constr. Build. Mater.* **2015**, *98*, 128–136.