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Effects of Steel Fiber Content and Maximum Coarse Aggregate Size on Mechanical Properties of Steel Fiber Reinforced Concrete

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Abstract

This research highlights the synergistic impact of including varying steel fiber contents and size of coarse aggregate on the concrete's mechanical characteristics, including compression strength, workability, splitting tensile strength, and stress-strain correlations under compression stress. The study investigated steel fiber percentages ranging from 0% to 2% with increments of 0.5% and coarse aggregate maximum sizes, namely (9.5mm, 12.5mm and 19mm). The study entailed the production and examination of a total of fifteen concrete samples, comprising three cubes and two cylinders for each concrete mixture. The results demonstrated that the compressive strength of concrete mixes lacking steel fibers shows a positive relationship with the largest size of coarse aggregate. However, the inclusion of steel fibers causes a reduction in compressive strength as the maximum size of coarse aggregate increases. Finer coarse aggregate sizes resulted in the highest tensile strength. Moreover, the study showed that including hooked-end steel fibers (SF) enhances the stiffness of concrete cylinders and allows for deformation without fracture. And, the influence of maximum coarse aggregate size on stress-strain behavior is negligible. These findings emphasize the significance of taking into account both the overall size and the inclusion of SF in mixes of concrete to improve the compressive and tensile strength, stress-strain responses, and overall performance.

Keywords— Maximum coarse aggregate size, SFRC, Mechanical properties, Concrete.

1 Introduction

It is common knowledge that brittle materials, such as normal concrete (NC), possess undesired qualities such as low tensile strength and restricted strain capacity. Conversely, flexible materials such as fiber-reinforced concrete (FRC), have a great resistance to being pulled apart and may bend, unlike brittle materials (Behbahani et al., 2011). FRC is a composite material composed of cement, coarse aggregates, fine aggregates, and discrete reinforcing fibers. The concrete might consist of mortars, standard concrete mixes, or mixtures tailored for a particular purpose. Various fibers such as steel, glass, and synthetic materials are utilized for reinforcing concrete and fibers that occur in nature. Steel fibers (SF) are the most often used kind of fibers (Ran et al., 2021). Hooked-end and crimped are the most prevalent forms of steel fibers (Khamees et al., 2020). Hooked-end steel fibers are superior than crimped and deformed fibers in terms of ductility (Liu & Yufei, 2007). Utilizing fiber reinforcement greatly increases the construction's long-term serviceability (Daniel et al., 2002).

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The primary benefits of fiber-reinforced concrete (FRC) are the prevention of microcracks from developing into macroscopic cracks, the Increase of ductility and residual strength after the first crack formation, and the application of fibers to increase strength, toughness, and durability (Abbass et al., 2018). Steel fibers enhance the mechanical characteristics of concrete but reduce its workability.Concrete's properties and performance are greatly affected by the aggregate's particle size and distribution. Moreover, concrete's fresh and hardened qualities are significantly impacted by maximum coarse aggregate size (American Concrete Institute, 1996;Meddah et al., 2010).

Grading refers to the arrangement of aggregate particles based on their various sizes. Aggregate gradations indicate the gaps and surface area of the aggregate that require filling and coating with cement paste. Grading can impact the mixture's economy by limiting the quantity of cement paste used. Grading is crucial because unworkable and difficult-to-compact concrete will not yield the intended results (Alexander & Mindess, 2005) (Mehta & Monteiro, 2006). The classification of aggregates affects the characteristics of both freshly mixed and hardened concrete. Mixtures that are easy to work with, transport, lay, and compress can be produced with well-graded aggregates. For (SFRC), the (ACI) committee 544 advises the utilization of mixed aggregate gradations. Some SFRC combinations have higher cement concentration and finer aggregate compared to conventional concrete, resulting in decreased workability as the percentage of fiber increases. Increasing the fiber percentage (Vf) and the maximum diameter can enhance the clustering of fibers and improve the strength of contact between concrete and steel fibers (Kim et al., 2012) (*State-of-the-Art Report on Fiber Reinforced Concrete*, 2002).

To enhance workability, SFRC necessitates elevating the paste content, constraining the maximum coarse aggregate size (Dmax) to a range of (10 to 38)mm, and refining the aggregate grading (*Guide for Specifying, Proportioning, Mixing, Placing, and Finishing Steel Fiber Reinforced Concrete*, 2005; *State-of-the-Art Report on Fiber Reinforced Concrete*, 2002). Many concrete aggregate grading standards provide gradations in terms of the percentage of mass that passes through specific testing with sieves. Moreover, standards incorporate graphs or logarithm grade curves that provide recommended limits for gradations. (Aggregates for Concrete, 2009; American Concrete Institute, 1996; American Society for Testing & Materials, 2003;).

A prior research (Akçaoğlu et al., 2002) and other research projects have done empirical inquiries into the influence of aggregate grading on fiber-reinforced concrete (FRC) (Han et al., 2019) (Ulas et al., 2017). The study found that the presence of steel fiber (SF) has a minimal impact on compression strength, but it has a substantial effect on tension strength. The compressive and tensile strengths exhibited an increase as the maximum coarse aggregate size rose, especially when using finer gradations.

Morteza Beygi et al. (Beygi, Kazemi, Vaseghi Amiri, et al., 2014) (Beygi, Kazemi, Nikbin, et al., 2014) have observed a similar pattern. Seok Joon, Jang and et al. (Jang et al., 2013) The study examined the impact of different maximum sizes of aggregate (8, 13, and 20)mm and percentages of fiber (0%, 1%, and 2%) on the flexural performance of high strength SFRC. The research showed that SFRC with a highest value of fibers and smaller size of coarse aggregate has significantly improved flexural properties.

According to Wu Yao et al. (Dai et al., 2004) , the impact of the ratio between the length of SF and the maximum size of coarse aggregates on (SFRC) is equally as important as the amount of steel fibers present. The recommendation is that the maximum coarse aggregate size in steel fiber reinforced concrete should not be more than 3/4 of the SF length or 25 mm (Hu et al., 2018).

This study aims to examine the link between maximum coarse aggregate size and SF coupling on the parameters of hardened and fresh mix of concrete, including workability, splitting tension strength, compression strength, and stress-strain relationship under compression stress. SF percentages of (0, 0.5, 1, 1.5 and 2%) and maximum coarse aggregate size ranging from 9.5mm to 19 mm have been employed in this study. In order to accomplish the objective of the study, three cubes and two cylinders were cast and examined for each concrete mixture to investigate the aforementioned properties.

2 Experimental program

The preparation of the material, testing of the material, mix proportions, casting, curing, and testing setup are all included in the experimental work.

2.1 Materials preparation

The normal concrete NC mixture comprises cement, sand, gravel (with three distinct sizes of coarse aggregate: 9.5, 12.5, and 19 mm), water, and a super-plasticizer. The SFRC mixture differs from the normal concrete (NC) mixture by including SF. The materials used in the project consist of Portland Cement, the fine aggregate used is pure sand, with a maximum particle size of 4.75 mm., and locally crushing maximum coarse aggregate size of 19, 12.5, and 9.5 mm. The three types of aggregates were separated and categorized based on the standard sieve series provided by the ASTM C33. Clean tap water, and a high-performance super-plasticizer concrete additive have be utilized in the production of all mixes. The inclusion of SF often reduces the workability of a cement matrix (Duhaim & Mashrei, 2024). Chemical admixtures can be utilized to preserve the workability of a combination without the need for additional water (American Concrete Institute, 1996) 11. A polycarboxylate-based superplasticizer (SP) additive was utilized for all combinations. The study employed hooked-end steel fibers measuring 35 mm in length and 0.55 mm in diameter. The fibers exhibited an aspect ratio (l/d) of 63.63 and a maximum tension strength of 1200 MPa, as stated by the maker business.

2.2 Mix proportions

The NC and SFRC design mix proportions are displayed in Table 1. The NC mixture was specifically designed (by the authors) to reach a 27 MPa cylinder compressive strength after 28 days.

Table 1: Mix proportions for 1 m^3 of concrete.

Materials	**Concrete type**	
	NC	**SFRC**
Cement (Kg)	400	400
Sand (Kg)	640	640
Gravel (Kg) 19mm, 12.5mm, 9.5mm	1010	1010
W/C Ratio	0.4	0.4
Steel Fiber (%)	0	0.5, 1, 1.5, 2
Superplasticizer (%)	0.6	0.6

2.3 Mixing procedure

The mixing process was conducted using laboratory mixers, which were properly cleaned and wetted before the use. The process of blending SFRC is analogous to that of NC. At first, a combination of aggregate and fine particles of sand were blended together. In addition, SF were manually incorporated into the dry mixture for an additional minute. Subsequently, cement was included into the combination, followed by the addition of two-thirds of the mixing water to the rotary mixer. Next, the super-plasticizer was added to the mixture, along with one-third of the mixing water. Subsequently, an extra four minutes was added to the mixing period to guarantee the even dispersion of SF in the new concrete.

After mixing, the homogeneous mixture of SFRC and NC with volume fractions of 0.5%, 1%, 1.5%, and 2% is shown in Figure 1.

NC SF =0.5% SF =1% SF =1.5% SF=2%

Figure 1: The influence of V_f of SF on the mix homogeneity of SFRC and NC

2.4 Casting and curing

Figure 2 illustrates the casting and curing procedures of the specimens, and Table 2 represents the examined samples. Initially, three cube specimens measuring 150*150*150 mm, two cylinder specimens measuring 150x300 mm were made for each mixture. Subsequently, a very thin coating of oil was sprayed to the inside surfaces of the mold to provide lubrication. Once all specimens were cast, they were immediately covered with plastic sheets. After two days, the plastic sheets were removed and the specimens were taken out of their molds. Subsequently, all specimens were fully submerged in water until they were ready for testing.

Figure 2: The casting and curing processes of samples

Table 2: Summary of the test program.

Mix Code	Maximum Coarse Aggregate Size (mm)	V_f of Steel Fibers (%)	Number of Cubes Tested	Number of Cylinders Tested
D19	19	0	3	2
		0.5	3	2
		1	3	2
		1.5	3	2
		2	3	2
D12.5	12.5	0	3	2
		0.5	3	2
		1	3	2
		1.5	3	2
		2	3	2
D9.5	9.5	0	3	2
		0.5	3	2

	1	3	2
	1.5	3	2
	2	3	2
Total		45	15

2.5 Testing the specimens

2.5.1 Compressive strength test

The compressive strength was determined by calculating the average value of three cubes of 150x150x150 mm. The test was carried out in compliance with BS EN 12390-3 (Standard, 2009), using a standard testing machine with a 2000 kN capacity. A constant load rate of 0.6 MPa per second was used for the test. Figure 3 illustrates the testing setup.

2.5.2 Splitting tensile strength test

The splitting tensile strength was measured by measuring the value of a single cylinder with dimensions of 150×300 mm. The test was carried out following the ASTM C496/C496M (*Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens*, 2017). The cylinder was exposed to a constant loading rate of 0.023 MPa per second until it reached its breaking point. The task was accomplished with a conventional testing apparatus with a maximum load capability of 2000 kilonewtons, as seen in Figure 3.

2.5.3 Compressive stress-strain test

The determination of the stress-strain relationships was based on the measurements collected from a single cylinder that had dimensions of 150×300 mm. The test was conducted following the standards ASTM C39/C39M (*Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*, 2014) and ASTM C469/C469M (*Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression*, 2014). This procedure required the use of two rigid circular rings that were firmly linked to one another at a height of about two-thirds of the cylinder by the utilization of clamping bolts. In order to determine the deformation that occurred in the central portion of the cylinder, a dial gauge that had a capacity of 25 millimeters and a precision of 0.01 millimeters was put between the rings. Within the context of a compression stress test, the experiment was carried out with a continuous loading rate of 0.3 MPa per second. Can be seen in Figure 3, a testing device that had a capacity of 2000 (kN) was used.

2.5.4 Modulus of elasticity (Ec)

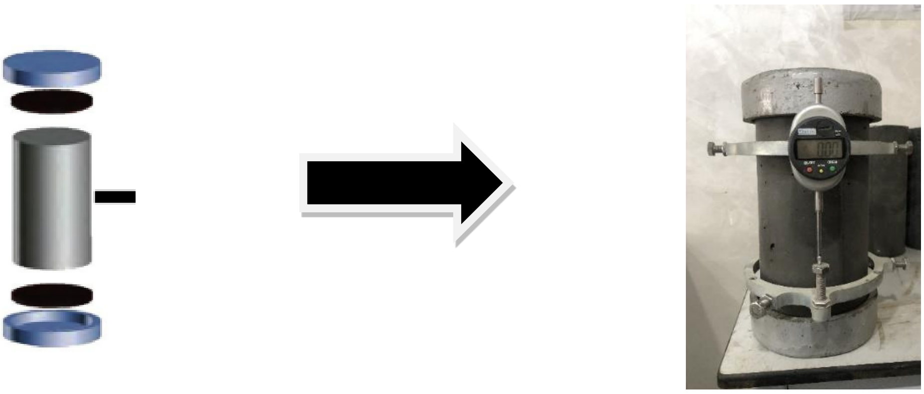
The static modulus of elasticity, which characterizes the material's stiffness, is one of the most significant characteristics of solid materials and should be understood. The materials and amounts used in the production of concrete have a significant impact on its elastic modulus (Khamees et al., 2020). By calculating the slope of the stress-strain curve between the stress at 40% of the compressive strength and the stress that corresponds to a strain of 0.00005, the modulus of elasticity was determined. This calculation was done following the guidelines of ASTM C469/C469M [32] using Equation (1).

$$E_c = \frac{s_2 - s_1}{\varepsilon_2 - 0.00005} \tag{1}$$

where:

- E_c is the static modulus of elasticity, MPa
- S_2 is the stress at 40% of compressive strength, MPa
- S_1 is the stress equal to 0.00005 of longitudinal strain, MPa
- ε_2= longitudinal strain produced by stress S_2.

(a) Standard testing machine for cubes and cylinders specimens



(b) Stress-strain test of cylinders

Figure 3: Testing machines for cubes and cylinders

3 Test results and discussion

3.1 Compressive strength

Table 3. displays the mean compressive strength of cubes for all tested concrete mixes. Figure 4, on the other hand, illustrates the various forms of failure seen in concrete cubes for different kinds of concrete. Table 3. shows that the compression strength of concrete mixes without steel fibers (NC) rises as the maximum coarse aggregate size increases. The increase in compression strength is directly proportional to the increase in maximum coarse aggregate size, which may be attributed to the larger amount of coarse material per unit volume of the mixture as maximum coarse aggregate size increases. These components increase the amount of the hard part in the mixture, which is responsible for enhancing strength (Seleem et al., 2020).

The addition of SF to concrete mixes results in a reversal, whereby the compression strength decreases as the maximum size of the aggregate increases. The size of the aggregate, 9.5 mm, had the biggest percentage rise of 35.02%, while the percentage of steel fibers was 2%. Additionally, the size of the aggregate, 12.5 mm, showed an increase of 30.21% when the steel fiber content was 2%, and the least increase in percentage of the same steel fiber content of 2% was seen with a maximum aggregate size of 19 mm. This occurs because when the maximum size of the coarse aggregate lowers, there is an increase in the number of granules that are trapped between the jaws of the steel fibers. Consequently, the bonding capacity between these granules is enhanced, resulting in an overall increase in strength. And in general, adding hooked-end steel fibers with Vf of (0.5,1, 1.5, and 2) % to NC improved the compressive strength.

Table 3: The mean compressive strength for various kinds of concrete.

Mix Code	Maximum Coarse Aggregate Size (mm)	V_f of Steel Fibers (%)	Compressive Strength (MPa) f_{cu}	The Increase in Compressive Strength (%)
D19	19	0	46.4	0
		0.5	49.6	6.89
		1	54.3	17.02
		1.5	58.00	25.00
		2	58.2	25.43
D12.5	12.5	0	46.0	0
		0.5	49.8	8.26
		1	55.6	20.86
		1.5	58.8	27.82
		2	59.9	30.21
D9.5	9.5	0	45.4	0
		0.5	51.5	13.43
		1	57.2	25.99
		1.5	59.7	31.49
		2	61.3	35.02

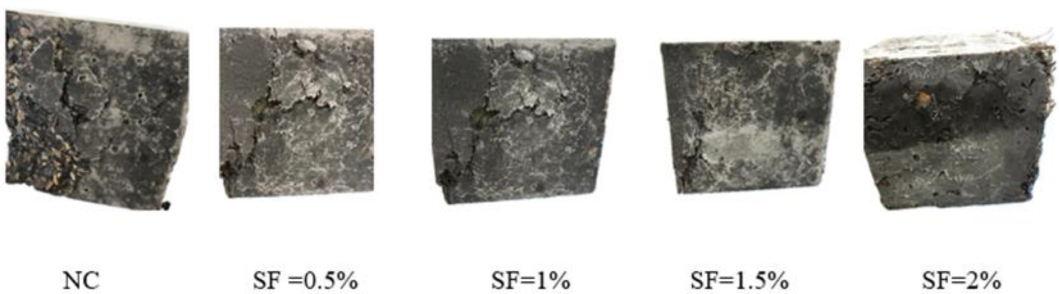


Figure 4: Modes of failure of concrete cubes

3.2 Splitting tensile strength

Table 4. shows the splitting tension strength of a single cylinder for various types of concrete. Figure 5 illustrates the different failure modes shown by concrete cylinders of various concrete types. Table 4. shows the inclusion of hooked-end steel fibers with varying volume fractions (0.5, 1, 1.5, and 2) % in concrete resulted in a more significant enhancement in the tensile strength, compared to the compressive strength of the SFRC. This may be associated with the process of preventing the propagation of cracks by using steel fibers to create bridges. The advantage of using steel fibers to enhance the tensile strength of concrete lies in their ability to halt cracks and transfer energy (Abbass et al., 2018). This effect is further amplified with higher concentrations of steel fibers. Furthermore, the utilization of hooked-end steel fibers enhances the adhesive strength between the fibers and the concrete matrix, hence enhancing the mechanical characteristics of (FRC), which is composed of components that are capable of being deformed without breaking.

The tensile strength is optimized when the aggregate is at its smallest maximum size, when used varying sizes. The highest tensile strength was seen with the max. aggregate size of 9.5 mm, compared to the sizes of 12.5 mm and 19 mm.

Table 4: Average splitting tensile strength for different concrete types.

Mix Code	Maximum Coarse Aggregate Size (mm)	V_f of Steel Fibers (%)	Tensile Strength (MPa) f_t	The Increase in Tensile Strength (%)
D19	19	0	3.20	0
		0.5	5.23	63.1
		1	6.75	110.0
		1.5	7.68	139.5
		2	8.48	164.5
D12.5	12.5	0	3.56	0
		0.5	5.3	48.8
		1	6.81	91.2
		1.5	7.98	124.1
		2	8.56	140.5
D9.5	9.5	0	3.718	0
		0.5	5.377	44.6
		1	6.85	84.2
		1.5	8.1	117.8
		2	8.78	136.1

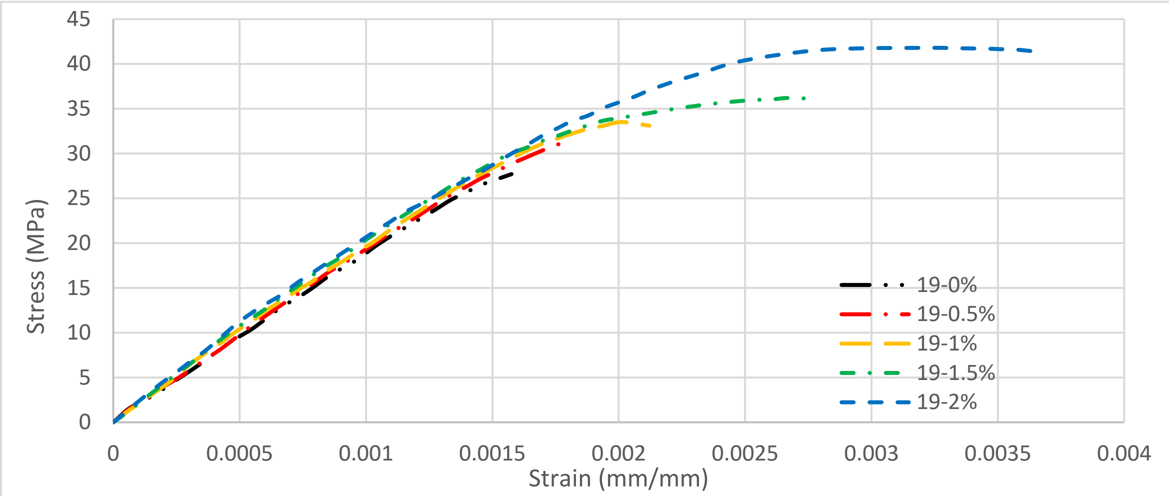
NC Vf =0.5% Vf =1% Vf =1.5% Vf =2%

Figure 5: Modes of failure of concrete cylinders under splitting stress (MAS 19mm)

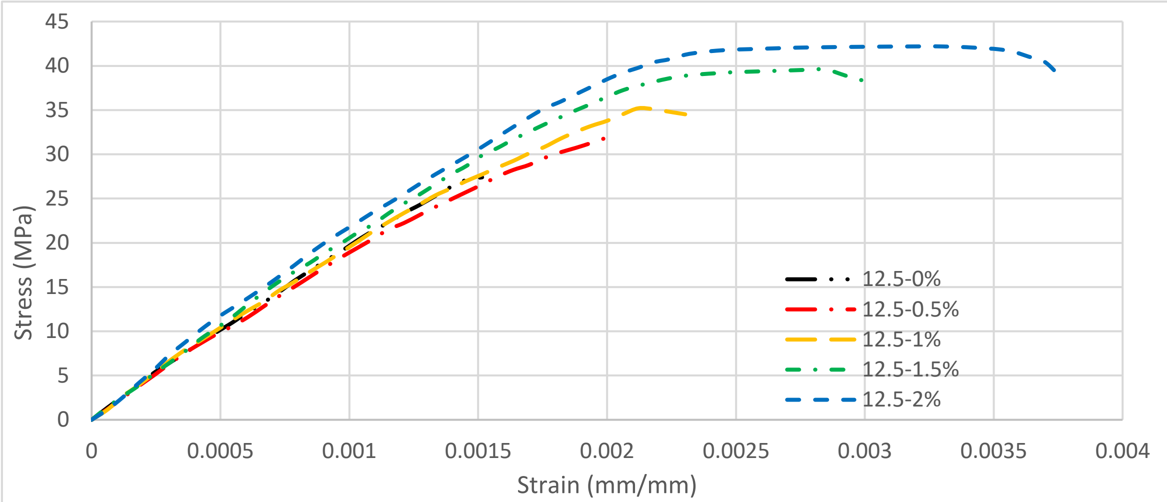
3.3 Stress-strain curves

Figure 6(a-c) displays the compressive stress-strain relationships for NC and SFRC. Figure 6 clearly demonstrates that the strain of all concrete cylinders exhibits a linear correlation with the increment of stress during the elastic stage. The strain observed during the elastic loading stage for ductile cylindrical materials appeared to be below the critical strain (NC), and the strain kept increasing after reaching the maximum stress with a slight increase in stress. The incorporation of hooked end steel fibers may be attributed to the improvement in the stiffness of these cylinders during the elastic loading stage and the enhancement of their capacity to undergo deformation without fracture during the ultimate stage.

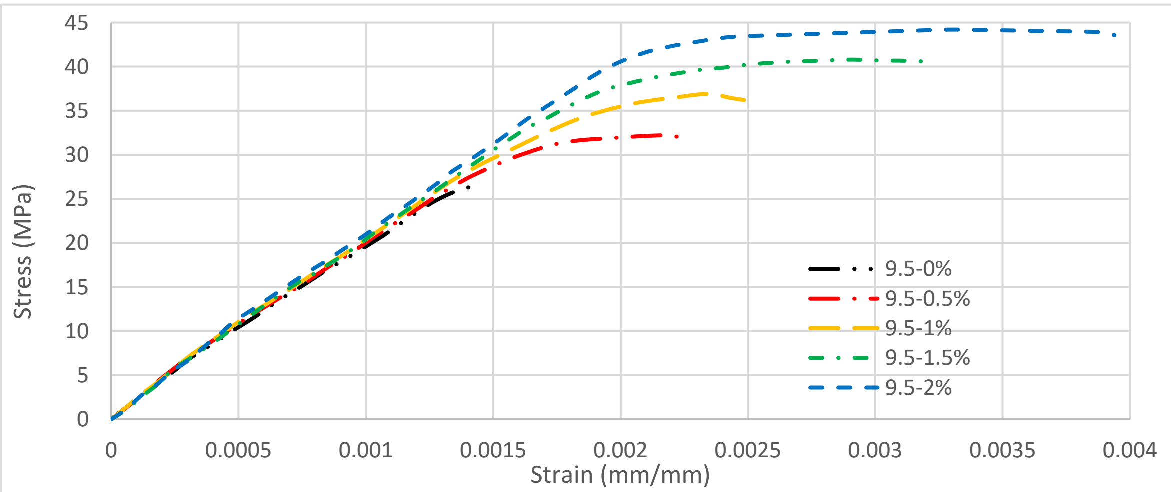
It is also obvious in Figure 6 (a-c) that the influence of the aggregate was very minimal, but the best behavior of the cylinders was obtained when utilizing the smallest maximum aggregate size (9.5 mm) compared to the other maximum sizes (12.5 mm and 19 mm).



(a)



(b)



(c)

Figure 6: Stress-strain relationships under compression for various types of concrete: (a) MAS 19 mm, (b) MAS 12.5 mm, (c) MAS 9.5 mm

Figure 7 illustrates two distinct failure mechanisms in cylinders for NC and SFRC. In the instance of NC, the cracks exhibited significant depth and were oriented in various directions, with a collapse occurring in the central region of the cylinder. However, many superficial fractures were noticed in SFRC cylinders close to the area of failure. The cracks did not cause significant damage to the cylinders, but there was some expansion in the central section. This indicates that the occurrence of ductile failure is a result of the utilization of steel fibers.

(a) (b) (c)

Figure 7: Failure modes of concrete cylinders subjected to compressive stress: (a) 19mm, (b) 12.5, (c) 9.5 mm.

3.3.1 Modulus of elasticity

The modulus of elasticity and compressive strength of cylinders for various concrete kinds are shown in Table 5.

Table 5: Modulus of elasticity values for different types of concrete.

Mix Code	Maximum Coarse Aggregate Size (mm)	V_f of Steel Fibers (%)	S1	S2	ε_2	Modulus of Elasticity, Ec (MPa)	The Increase in Modulus of Elasticity (%)
D19	19	0	1.239	11.08	0.000580	18567	0
		0.5	1.180	12.52	0.000635	19384	4.4
		1	1.070	13.40	0.000666	20016	7.8
		1.5	1.000	14.48	0.000690	21062	13.4
		2	1.166	16.72	0.000750	22228	19.7
D12.5	12.5	0	1.731	10.96	0.000543	18719	0
		0.5	0.900	12.76	0.000648	19838	5.79
		1	0.933	14.08	0.000702	20164	7.7
		1.5	1.160	15.84	0.000739	21306	13.8
		2	0.933	16.88	0.000759	22492	20.1
D9.5	9.5	0	1.842	10.8	0.000519	19100	0
		0.5	1.457	12.88	0.000611	20362	6.6
		1	1.092	14.76	0.000701	20995	9.9
		1.5	0.900	16.32	0.000754	21906	14.6
		2	0.890	17.68	0.000793	22592	18.2

Table 5. demonstrates that including hooked-end steel fibers with NC resulted in a significant increase in the modulus of elasticity of concrete. Specifically, at a maximum coarse aggregate size of 19mm, the modulus of elasticity increased by 4.4%, 7.8%, 13.4%, and 19.7% for fiber volume fractions of 0.5%, 1%, 1.5%, and 2%,

respectively. The modulus of elasticity for a maximum coarse aggregate size of 12.5mm increased by 5.79%, 7.7%, 13.8%, and 20.1% of Vf values of 0.5%, 1%, 1.5%, and 2% respectively, compared to the reference material (NC). Similarly, the modulus of elasticity for a maximum coarse aggregate size of 9.5mm increased by 6.6%, 9.9%, 14.6%, and 18.2% of Vf values of 0.5%, 1%, 1.5%, and 2% respectively, compared to NC. This is due to the fact that ductile materials have a higher strength than NC.
It should be noted that the maximum size of the coarse aggregate has a slight impact, resulting in a minor enhancement of the compressive strength in the steel fiber-reinforced cubes, as well as a slight improvement in the compressive and tensile strength of the steel fiber-reinforced cylinders.

4 Conclusions

Concrete mixes without steel fibers show an increase in compressive strength as the maximum size of coarse aggregate increases. The rise is exactly proportional to the increase in maximum aggregate size (MAS). The increase in the solidification stage of the concrete mixture adds to the improvement in strength.

- The effect of steel fibers on increasing compressive strength becomes less when using a large maximum size of coarse aggregate. The decrease is substantial, with the most notable increase in compressive strength seen when using a 9.5 mm aggregate size and 2% steel fiber content. This effect arises due to the fact that smaller aggregate sizes lead to heightened bonding between granules that are trapped between steel fibers, thereby augmenting the total strength.
- The addition of hooked-end steel fibers, at different volume fractions, greatly enhances tensile strength in comparison to the compressive strength. The enhancement is ascribed to the steel fiber's capacity to form bridges and hinder the spread of cracks. Increased concentrations of steel fibers significantly augment the adhesive strength between fibers and the concrete matrix, hence enhancing the mechanical properties of Fiber Reinforced Concrete (FRC).
- The optimal tensile strength is achieved while using the smallest possible maximum aggregate size. More precisely, the highest level of tensile strength is seen when the aggregate size is 9.5 mm, as opposed to greater sizes of 12.5 mm and 19 mm.
- The utilization of hooked-end steel fibers enhances the stiffness of concrete cylinders under elastic loading and increases their ability to undergo deformation without breaking at the final stage. The impact of aggregate size on stress-strain behavior is negligible, with the most optimal results seen when using the smallest maximum aggregate size.

These findings highlight the substantial impact of both the maximum size of the aggregate and the inclusion of steel fibers on the mechanical characteristics of concrete, specifically in relation to its compressive and tensile strength, stress-strain response.

5 References

Abbass, W., Khan, M. I., & Mourad, S. (2018). Evaluation of mechanical properties of steel fiber reinforced concrete with different strengths of concrete. *Construction and Building Materials*, *168*, 556–569. https://doi.org/10.1016/j.conbuildmat.2018.02.164

Aggregates for Concrete. (2009). British Standards Institution (BSI). https://www.bsigroup.com

Akçaoğlu, T., Tokyay, M., & Çelik, T. (2002). Effect of coarse aggregate size on interfacial cracking under uniaxial compression. *Materials Letters*, *57*(4), 828–833. https://doi.org/10.1016/S0167-577X(02)00881-9

Alexander, M., & Mindess, S. (2005). *Aggregates in concrete*. CRC Press.

American Concrete Institute. (1996). *State-of-the-Art Report on Fiber Reinforced Concrete* (Reapproved 2009).

American Society for Testing, & Materials. (2003). *Annual Book of ASTM Standards*. American Society for Testing and Materials (ASTM). https://www.concrete.org

Behbahani, H. J., Nematollahi, B., & Farasatpour, M. (2011). *Steel fiber reinforced concrete : a review*.

Beygi, M. H. A., Kazemi, M. T., Nikbin, I. M., Vaseghi Amiri, J., Rabbanifar, S., & Rahmani, E. (2014). The influence of coarse aggregate size and volume on the fracture behavior and brittleness of self-compacting concrete. *Cement and Concrete Research*, *66*, 75–90. https://doi.org/10.1016/j.cemconres.2014.06.008

Beygi, M. H. A., Kazemi, M. T., Vaseghi Amiri, J., Nikbin, I. M., Rabbanifar, S., & Rahmani, E. (2014). Evaluation of the effect of maximum aggregate size on fracture behavior of self compacting concrete. *Construction and Building Materials*, *55*, 202–211. https://doi.org/10.1016/j.conbuildmat.2014.01.065

Dai, M., Gai, Y. F., Zhang, J. H., & Liu, B. L. (2004). Study of flexural toughness of steel fiber reinforced concrete. *Journal of Shenyang Jianzhu University*, *20*(4), 308–311.

Daniel, J. I., Gopalaratnam, V. S., Galinat, M. A., Ahmad, S. H., Hoff, G. C., Schupack, M., Arockiasamy, M., Jindal, R. L., Shah, S. P., & Balaguru, P. N. (2002). Report on fiber reinforced concrete. *Reported by ACI Committee*, *544*.

Duhaim, H. M., & Mashrei, M. A. (2024). The effect of using steel fibers reinforced concrete layer in compression zone on the flexural behavior of over-reinforced concrete beams. *Structural Concrete*, *25*(1), 456–472. https://doi.org/10.1002/suco.202200675

Guide for Specifying, Proportioning, Mixing, Placing, and Finishing Steel Fiber Reinforced Concrete (Reapproved 1998). (2005). American Concrete Institute. https://www.concrete.org

Han, J., Zhao, M., Chen, J., & Lan, X. (2019). Effects of steel fiber length and coarse aggregate maximum size on mechanical properties of steel fiber reinforced concrete. *Construction and Building Materials*, *209*, 577–591. https://doi.org/10.1016/j.conbuildmat.2019.03.086

Hu, F., Chen, G., Gao, D., Zhao, K., & Zhang, C. (2018). Mechanical Properties of Steel Fiber-Reinforced Magnesium Phosphate Cement Mortar. *Advances in Civil Engineering*, *2018*.

Jang, S. J., Yun, Y. J., & Yun, H. Do. (2013). Influence of Fiber Volume Fraction and Aggregate Size on Flexural Behavior of High Strength Steel Fiber-Reinforced Concrete (SFRC). *Applied Mechanics and Materials*, *372*, 223–226. https://doi.org/10.4028/www.scientific.net/AMM.372.223

Khamees, S. S., Kadhum, M. M., & Alwash, N. A. (2020). Effects of Steel Fibers Geometry on the Mechanical Properties of SIFCON Concrete. *Civil Engineering Journal*, *6*(1), 21–33. https://doi.org/10.28991/cej-2020-03091450

Kim, J. J., Kim, D. J., Kang, S. T., & Lee, J. H. (2012). Influence of sand to coarse aggregate ratio on the interfacial bond strength of steel fibers in concrete for nuclear power plant. *Nuclear Engineering and Design*, *252*, 1–10. https://doi.org/10.1016/j.nucengdes.2012.07.004

Liu, K., & Yufei, W. U. (2007). Compression yielding by SIFCON block for FRP-reinforced concrete beams. *Asia-Pacific Conference on FRP in Structures (APFIS 2007)*, 411.

Meddah, M. S., Zitouni, S., & Belâabes, S. (2010). Effect of content and particle size distribution of coarse aggregate on the compressive strength of concrete. *Construction and Building Materials*, *24*(4), 505–512. https://doi.org/10.1016/j.conbuildmat.2009.10.009

Mehta, P. K., & Monteiro, P. (2006). Concrete: microstructure, properties, and materials. *(No Title)*.

Ran, J., Li, T., Chen, D., Shang, L., Li, W., & Zhu, Q. (2021). Mechanical properties of concrete reinforced with corrugated steel fiber under uniaxial compression and tension. *Structures*, *34*, 1890–1902. https://doi.org/10.1016/j.istruc.2021.08.135

Seleem, M. H., Badawy, A. A., & Mohamed, S. S. (2020). Effect of Maximum Aggregate Size on the Mechanical Properties and Flexural Energy of FRC. *Al-Azhar University Civil Engineering Research Magazine (CERM)*, *42*(1), 86–94.

Standard, B. (2009). Testing hardened concrete. *Compressive Strength of Test Specimens, BS EN*, 12390–12393.

Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. (2014). https://www.astm.org

Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens (Issue ASTM C496/C496M). (2017). https://www.astm.org

Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression (Issue ASTM C469/C469M). (2014). https://www.astm.org

State-of-the-Art Report on Fiber Reinforced Concrete (Reapproved 2005). (2002). American Concrete Institute. https://www.concrete.org

Ulas, M. A., Alyamac, K. E., & Ulucan, Z. C. (2017). Effects of aggregate grading on the properties of steel fibre-reinforced concrete. *IOP Conference Series: Materials Science and Engineering*, *246*, 012015. https://doi.org/10.1088/1757-899X/246/1/012015