2024 Scienceline Publication

*Journal of Civil Engineering and Urbanism*

Volume 14, Issue 3S: 238-246; September 25, 2024

ISSN-2252-0430

DOI: https://dx.doi.org/10.54203/jceu.2024.25

# Performance-Based Evaluation of Steel Fibre Reinforced Normal- and High-Strength Concretes Using Statistical Analysis of Experimental Database

**Adekunle P. Adewuyi**, and **Odette Animbom**

*Department of Civil Engineering, University of Botswana, Gaborone, Botswana*

Corresponding author's Email: AdewuyiA@ub.ac.bw

RESEARCH ARTICLE
PII: S225204302400025-14
Received: June 25, 2024
Revised: September 02, 2024
Accepted: September 05, 2024

**ABSTRACT**

The widespread acceptance of concrete can be attributed to its unique characteristics, despite inherent drawbacks such as brittleness and weak tensile strength. The study was aimed at evaluating the optimal content and characterization of steel fibres required to impede crack propagation and enhance overall strength of concrete. The influence of critical factors like fibre content, length, diameter, and volume fraction on the performance of steel fibre reinforced concretes (SFRC) through statistical analysis of 209 experimental data. The influence of these factors on the compressive, flexural, and tensile strengths of concrete was analyzed as a function of the mean and coefficient of variation of the normalized strength values. The study found that steel fibres in concrete produced success rates of 67.9% (7.1% average strength improvement = ASI) in compressive strength, 78.5% (38.2% ASI) in flexural strength and 84.2% (23.8% ASI) in tensile strength. The study further separately examined the impact of steel fibres on both normal strength concretes (NSC) and high strength concretes (HSC). The findings indicated an overall success rate of 60% (6.97% ASI), 69.9% (38.36% ASI), and 75.6% (23.59% ASI) for compressive, flexural, and split tensile strength, respectively, in NSC. However, higher degree of strength enhancement of 74.0% (7.16% ASI), 84.8% (39.21% ASI), and 86.6% (23.51% ASI) were recorded for compressive, flexural, and split tensile strength, respectively in HSC. The research underscores the effectiveness of incorporating steel fibres as a reinforcement strategy in enhancing various strength aspects of concrete.

**Keywords:** Fibre reinforced concrete, steel fibres, compressive strength, tensile strength, flexural strength, normalized strength, average strength improvement.

## INTRODUCTION

Concrete is practically the most widely used construction material, which contributes immensely to global economic growth and infrastructural development (Adewuyi et al., 2015). However, concrete has low flexural and tensile strength and lacks the ability to resist cracks (Kim et al., 2019; Sidiq et al., 2019). The incorporation of fibers into concrete matrices, to produce fiber reinforced concrete (FRC) has been found to enhance the tensile and flexural strength of concrete. Steel fibre reinforced concrete (SFRC) is a composite material comprising of cement, fine and coarse aggregates, and discrete discontinuous steel fibres (Zhang et al., 2014; Balagopal et al., 2022). Numerous studies have reported the influences of incorporating steel fibres on the mechanical properties of concrete, but the research findings differ across different studies. Consequently, this study embarks on a comprehensive performance-based analysis of SFRCs through the application of statistical analysis to an extensive experimental database. The aim of the study was to systematically evaluate the influence of key parameters namely the type of steel fibre, the percentage fiber content or volume fraction, the fibre geometry (i.e. the length, diameter or the aspect ratio of fibre) on the mechanical and durability properties of SFRC from normal and high strength concrete. This sheds light on the intricate interactions between the constituents and their impact on overall performance.

## MATERIALS AND METHODS

### Data extraction from experimental studies

The database of 209 experimental investigations conducted on steel FRC of a large variety of concrete mixes, covered various ranges of compressive strength of the mixes, volume fraction of the fibres, fibre aspect ratio, fibre tensile strength and modulus of elasticity. The criteria considered for selection of suitable experimental data from relevant literature included the impact factor, publication year, and citation count. Data documented only in specialized research publications in high quality journals of impact factors of 0.554 – 7.675, of citations ranging from zero (for the most recently published articles) to 1103 within the publication years 2010 to 2023. Table 1 shows the properties of concrete, steel fibres and fibre content in the SFRC experimental programme.

Control specimens accounted for 17.2% of the total sample size. Figure 1 shows the graphical distribution of the SFRC in terms of the fibre geometry was hooked – 82%, straight – 9%, corrugated – 3%, crimped – 2%, closed – 2% and round ended steel fibres – 1%. It also evident from Figure 1(b) that the corrugated steel fibre had the highest strength enhancement of 82.6% (for flexure) and 68.1% (for tension), followed by straight, hooked, crimped, closed and the least enhanced fibre was the round steel fibres. While no steel fibre compromised the compressive strength threshold, the maximum enhancement was 14% (for round steel fibre), followed by hooked (9.03%), corrugated (8%), straight (6.9%), crimped (5.1%) and the least was closed steel fibre (2.7%). Moreover, in terms of the success rate or otherwise as shown in Figure 1(c), all the FRC samples concrete scrimped and closed steel fibers recorded 100% success rates in compression, flexure and tension. Straight and corrugated SFRCs recorded 100% success rates in flexure and tension, while there were 15% and 16.7% failure rates for samples in compression. Hooked FRCs samples all passed the tensile strength threshold, but 17.8% and 4.27% of the samples fell short in compression and flexure. Finally, all the round steel FRCs passed compressive strength assessment, but only one-half of the samples passed the flexural strength limit.

Fibres were classified as normal strength (≤50 MPa) and high strength (> 50 MPa) according to Eurocode 2. Data collection criteria included impact factor, publication year, and citation count. The experimental database comprises 90 samples normal strength concrete (43% of entire experimental data), while high strength concrete (119 samples) accounted for the remaining 57%.

**Table 1**. Properties of the steel fibres

| Properties | Values |
|---|---|
| Concrete compressive strength (MPa) | 18-195 |
| Volume fraction (%) | 0.05-5 |
| Fibre length (mm) | 13-130 |
| Fibre diameter (mm) | 0.2-1.6 |
| Tensile strength of fibres (MPa) | 250-2660 |
| Elastic modulus of fibres (GPa) | 200-210 |

**Evaluation of strength enhancement based on normalization of test data**

The data was normalized with respect to the control to account for different concrete grades in the experimental dataset. This created a benchmark for analysis, where values below one meant decreased strength, values at one showed no improvement, and values above one indicated increased strength.

The normalized strength ratio (NSR) is expressed as the ratio of strength of fibre reinforced concrete to the strength of plain concrete without fibre.

(1) $$NSR = \frac{\text{Strength of fibre reinforced concrete}}{\text{Strength of equivalent grade of plain content}}$$

The normalized strength ratio (NSR) is expressed in terms of the compressive, tensile and flexural strengths designated as NCS, NTS and NFS.

(2) Normalized compressive strength, $NCS = \frac{f'_{ck}}{f'_{ck0}}$

(3) Normalized tensile strength, $NTS = \frac{f'_{ct}}{f'_{ct0}}$

(4) Normalized flexural strength, $NFS = \frac{f'_{cf}}{f'_{cf0}}$

where $f'_{ck0}$, $f'_{ct0}$ and $f'_{cf0}$ are compressive, tensile and flexural strength of plain concrete (with no fibres) respectively. Likewise, $f'_{ck}$, $f'_{ct}$ and $f'_{cf}$ are compressive, tensile and flexural strength of fibre reinforced concrete respectively.

**Degree of success and failure**

The efficiency of FRC is measured as the extent to which the normalization exceeds a threshold of 1. Hence the success rate (SR) and the failure rate (FR) is calculated as given by equations (5) and (6). A sample is said to be successful when NSR ≥ 1, while a failed sample has NSR < 1. The optimal constituent parameters are then determined by accessing the degree of success based on the frequency of the parameters that produced the best strength efficiency of FRC.

The success rate is determined as the percentage ratio of the successful samples to the entire population size of investigated samples, while failure rate was calculated as the percentage ratio of failed samples to the entire population size. The calculation of success and failure involved applying the formulae.

(5) $$\text{Success rate (SR)} = \frac{\text{Number of successful samples}}{\text{Total population size}} \times 100\%$$

(6) $$\text{Failure rate (FR)} = \frac{\text{Number of failed samples}}{\text{Total population size}} \times 100\%$$

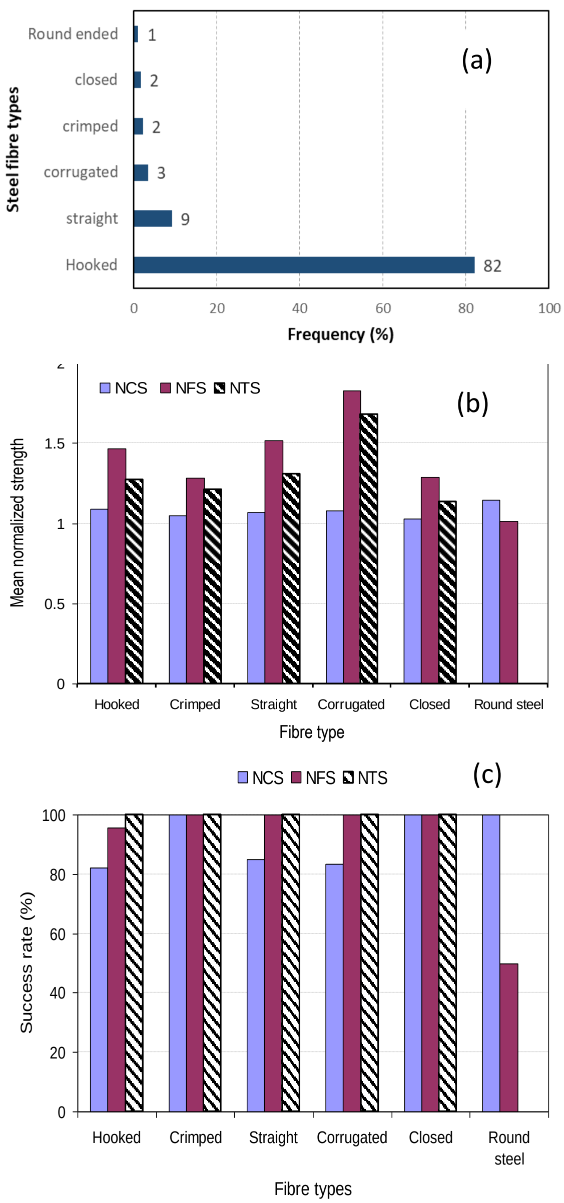


**Figure 1.** Distribution, mean normalized strengths and efficiency of different steel fibres in SFRC experimental scheme

## RESULTS AND DISCUSSION

### Statistical description of data distribution

Table 2 shows the statistical parameters in terms of the mean, standard deviation, coefficient of variance, skewness and kurtosis values for the normalized compressive, tensile and flexural strength for steel fibre reinforced concretes. It is evident from the findings that introduction of fibres in plain concrete enhanced the flexural and tensile properties by 38.2% and 23.8% respectively, while the compressive strength was only improved by a single digit 7.1%. The coefficient of variation of the data were within the 30% reliability bracket.

**Table 2.** Statistical parameters of the normalized strengths of hardened steel FRC

| Statistical parameter | Mean | Standard deviation | CoV (%) |
|---|---|---|---|
| Compressive strength | 1.071 | 0.117 | 11 |
| Flexural strength | 1.382 | 0.399 | 28.8 |
| Tensile strength | 1.238 | 0.237 | 19.2 |

### Effect of fibre volume fraction on concrete properties

Figure 2 presents the performance of SFRC in terms of the normalized strength values and the success/failure rate of different volume fractions of embedded steel. The performance of the SFRC in terms of the volume fraction is presented for compression, flexure and tension in the subsequent sections, while Figure 2(d) shows that fibre volume content range 1.0 to 1.5% produced the optimal performance and by extension the highest success rate.

***Compressive strength***

Some literature indicates that adding steel fibre to concrete can enhance compressive strength by 4-19% (Ali et al., 2022; Zhang et al., 2020). However, studies also suggest that steel fiber under 1.0% may not significantly impact compressive strength (Rizzuti & Bencardino, 2014; Soulioti et al., 2011). Figure 2 presents the influence of the volume fraction of different geometric properties and shapes of steel fibres on the normalized strengths of FRC. Figure 2(a) illustrates the impact of steel fibre volume fraction on concrete's compressive strength. Optimal strength enhancement was achieved at 1.5% volume fraction. Nonetheless, within the 0.5-2% range, the data consistently provided useful insights, particularly highlighting 1.5% as yielding the highest average increase of 15.68%. Additionally, it demonstrated a success rate of 86.96% alongside a 13.04% failure rate.

***Flexural strength***

The flexural strengths of SFRC are reported to be significantly higher, ranging from 3% to 81% greater than those of the reference mixture (Ali et al., 2022; Zhang et al., 2020). This is due to the bridging effect of the fibers, which inhibits fracture propagation and enhances flexural performance through stress redistribution (Jun et al., 2023). Figure 2(b) quantifies the influence of volume fraction of steel fibers on the flexural strength of FRC. The most significant improvement was observed at 1.5%

volume fraction. However, data points were well-distributed across 0.5%, 1%, and 2% volume fractions. Notably, 1.5% (98.87% average increase) and 2% (61.12% average increase) fiber volumes exhibited the most substantial enhancements. It was found that while both 1.5% and 2% showed a 100% success rate, the average strength enhancement was higher at 1.5%.

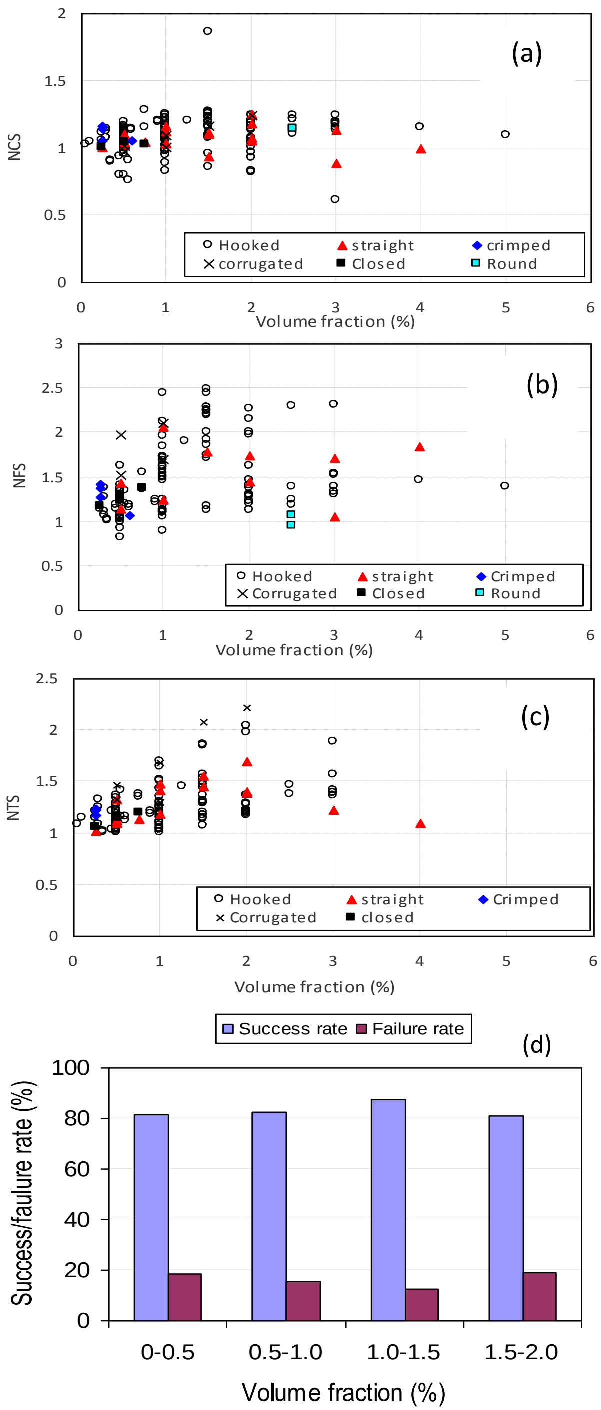


**Figure 2.** Normalized compressive, flexural and tensile strength of SFRCs with respect to the volume fraction

***Split tensile strength***

According to various studies, the inclusion of steel fibers in concrete has been shown to notably enhance the split tensile strength of the material surpassing the reference mixture by approximately 11–54% (Ali et al., 2022; Zhang et al., 2020). Figure 2(c) illustrates the impact of steel fiber volume fraction on concrete's tensile strength. The highest enhancement was observed at a 2% fiber content, resulting in a 47.16% increase and a 100% success rate. However, data points were well- distributed across 0.5%, 1%, and 1.5% volume fractions, resulting in respective increases of 17.63%, 28.41%, and 41.77% in NTS. These findings highlight a positive correlation between NTS and fiber volume, with the optimum volume identified as 2%.

**Effect of fibre length on concrete properties**

***Compressive strength capacity of FRC***

Figure 3 shows the effects of fibre length on the strength of concrete in compression, tension and flexure. As shown in Figure 3(a), most of the data points were within the volume fractions of 0-0.5%, 0.5-1.0%, 1.0-1.5% and 1.5-2.0%. The subsequent analysis focused solely on these specific volume fractions. Table 3 summarizes the success rates and failure rates in enhancing compressive strength. The highest success rate is achieved at the volume fraction range of 1.0 to 1.5.The optimal fibre lengths within this range, contributing to an enhanced compressive strength, was found to be between 30-60 mm resulting in a 19.36% increase in compressive strength.

**Table 3.** Summary of success and failure rates for compressive strength of SFRC.

| Volume fraction | Success rate (%) | Failure rate (%) |
|---|---|---|
| 0-0.5 | 81.48 | 18.52 |
| 0.5-1.0 | 82.35 | 15.68 |
| 1.0-1.5 | 87.5 | 12.5 |
| 1.5-2.0 | 80.95 | 19.05 |

***Tensile performance of FRC at different fibre lengths***

Figure 3(b) illustrates the impact of steel fibre length on the split tensile strength of concrete. By observation, most data points were within the volume fractions of 0 to 0.5%, 0.5 to 1.0%, and 1.0 to 1.5 %. The analysis focused solely on these specific volume fractions. Table 4 summarises the success and failure rates in enchancing the split tensile strength. There is a 0% failure rate for all fibre volume fraction ranges. The average increase in the tensile strength is 15.93, 26.83%, 41.96%, and Considering the increase, the range from 1.0 to 1.5% offers the best enhancement. The optimal fibre lengths within this range, contributing to an enhanced split tensile strength, were found to be in the range of 30-60 mm.

**Table 4.** Summary of success and failure rates for split tensile strength of SFRC.

| Volume fraction | Success rate (%) | Failure rate (%) |
|---|---|---|
| 0-0.5 | 100 | 0 |
| 0.5-1.0 | 100 | 0 |
| 1.0-1.5 | 100 | 0 |
| 0-0.5 | 100 | 0 |

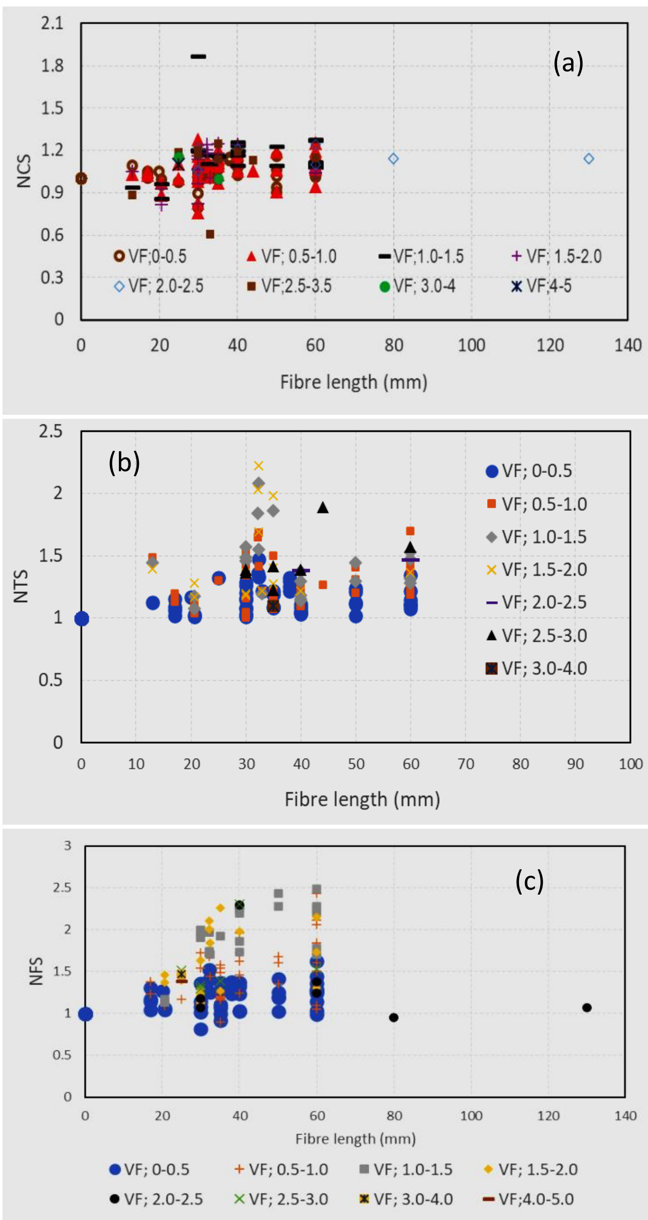


**Figure 3**. Normalized compressive, flexural and tensile strength of SFRC with respect to fibre length.

**Flexural assessment of FRC at varying fibre lengths**

The effects of steel fiber lengths on concrete flexural strength are illustrated in Figure 3(c). Most data points clustered within volume fractions of 0 to 0.5%, 0.5 to 1.0%, and 1.0 to 1.5% brackets. The analysis concentrated specifically on these volume fractions is summarised in Table 5. Noting that the 1-1.5% range yielded the highest average increase in flexural strength of 96.58%. Considering this, and keeping the volume fraction at the optimum 1.5%, the most impactful lengths within this range were 30 mm, 40 mm, 50 mm, and 60 mm, resulting in respective increases of 95.5%, 105.7%, 136.0%, and 111.9%. The findings indicated a positive correlation between length and flexural strength, with 50 mm identified as the optimal length.

**Table 5.** Summary of success and failure rates for flexural strength of SFRC.

| Volume fraction | Success rate (%) | Failure rate (%) |
|---|---|---|
| 0-0.5 | 91.11 | 8.89 |
| 0.5-1.0 | 97.67 | 2.33 |
| 1.0-1.5 | 100 | 0 |

**Effect of fibre diameter on concrete properties**

***Influence of fibre size on compressive strength***

Figure 4(a) depicts the influence of fibre diameter on the mechanical properties SFRCs. The preceding analysis has shown that 1.0-1.5% volume fraction is the most beneficial and effective volume fraction for SFRCs.

Within this range, maintaining a volume fraction of 1.5%, key fiber diameters were around 0.5 mm, 0.62 mm, 0.75 mm, and 1.03 mm, resulting in average NCS of 1.1941, 1.1782, 1.1648, and 0.9059. These values correspond to strength enhancement of 19.41%, 17.82%, 16.48%, and a reduction of 9.41% in NCS, respectively for the four classes of fibre diameters. The findings revealed that the compressive strengths decrease as the size of the fibre increase, where 0.5 mm was the optimal diameter.

***Influence of fibre diameter on tensile strength of SFRC***

The effect of steel fibre diameter on the split tensile strength of SFRC is illustrated in Figure 4(b). Having concluded from preliminary assessment of volume fraction and its effect on the mechanical properties of SFRC, 1-1.5% volume fraction was found as the optimal fibre content in FRC. Building the investigation on the optimal volume fraction of 1.5% for different fibre sizes 0.55 mm, 0.75 mm, 1.03 mm, and 1.05 mm, the average split tensile strength corresponds to an enhancement of 53.4%, 36.4%, 22.8%, and 21.9%, respectively. The results indicate that the average tensile strength of SFRCs decrease as the fibre length increased. diameter increases. The optimum fibre diameter to achieve the most enhanced split tensile strength was 0.55 mm.

***Influence of fibre diameter on flexural strength of SFRCs***

Figure 4(c) presents the influence of fibre diameter on the flexural strength of concrete. For the established optimal fibre volume of 1.0-1.5%, the normalized flexural strength corresponding to the key diameters 0.5 mm, 0.62 mm, 0.75 mm, and 1.03 mm were 0.95, 1.21, 1.20 and 1.05 respectively. The results demonstrate a positive parabolic correlation such that the flexural strength increases with fibre diameter and attained the maximum NFS of 1.225 (or 22.5% strength enhancement) at optimum fibre size of 0.65 mm.

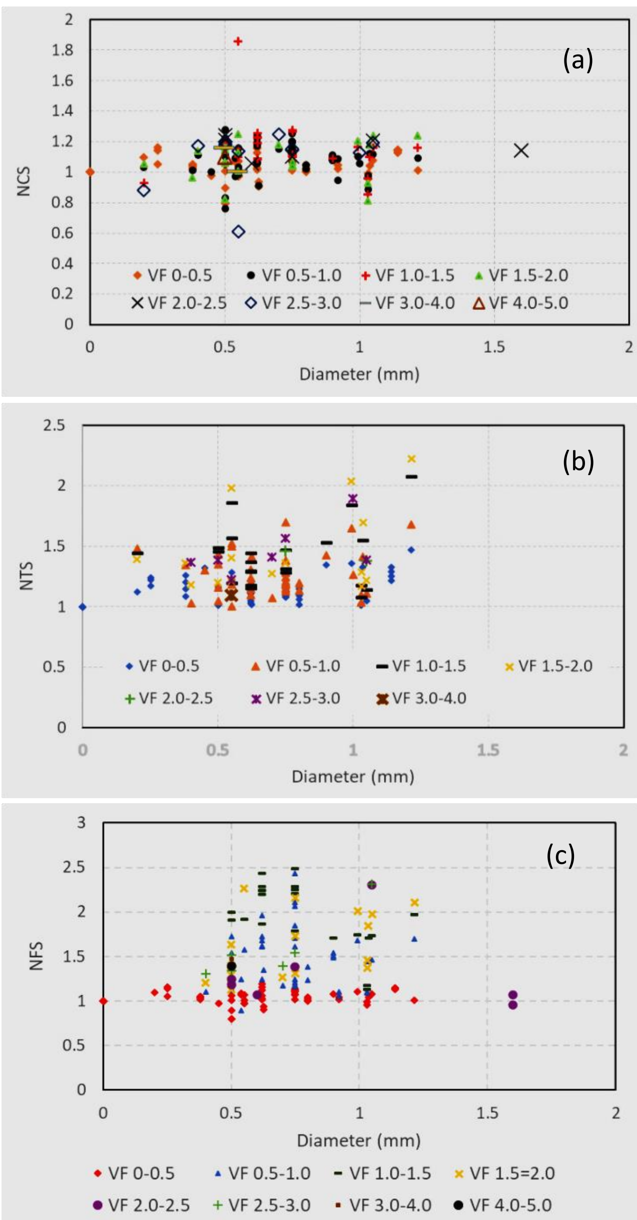


**Figure 4.** Normalized compressive, flexural and tensile strength of SFRC with respect to fibre diameter.

**Performance of SFRC Based on normal and high strength concrete**

Many experimental investigations have been conducted on fibre reinforced concretes based on different grades of concrete. These concrete grades can be categorized into the normal strength concrete (NSC) with characteristic compressive cylinder strength of concrete not exceeding 50 N/mm$^2$, while the high strength concrete (HSC) have compressive cylinder strength greater than 50 N/mm$^2$. It has been established in the preceding sections that though the introduction of fibres improve the tensile and flexural capacities of SFRC, it ocasionally does so at the expense of the compressive strength. The following sub-sections describe the influence of that grade of concrete on the overall performance of steel FRC.

***Influence of concrete grade on the compressive strength of SFRCs***

The scattered plots of the normalized compressive strength (NCS) of steel FRC of varying volume fractions for the normal- strength concrete (NSC) and high-strength concrete (HSC) are shown in Figure 5(a) and Figure 5(b) respectively. The NSC produced an average increase of 4.41% in the compressive strength, while only 14.19% of the samples fell below the control threshold. On the other hand, the HSC exhibited an average 9.11% enhancement in compressive where 12.6% fell below the control compressive strength. It is therefore evident that FRC performed slightly better in concrete of high grade compared to the normal strength concrete.

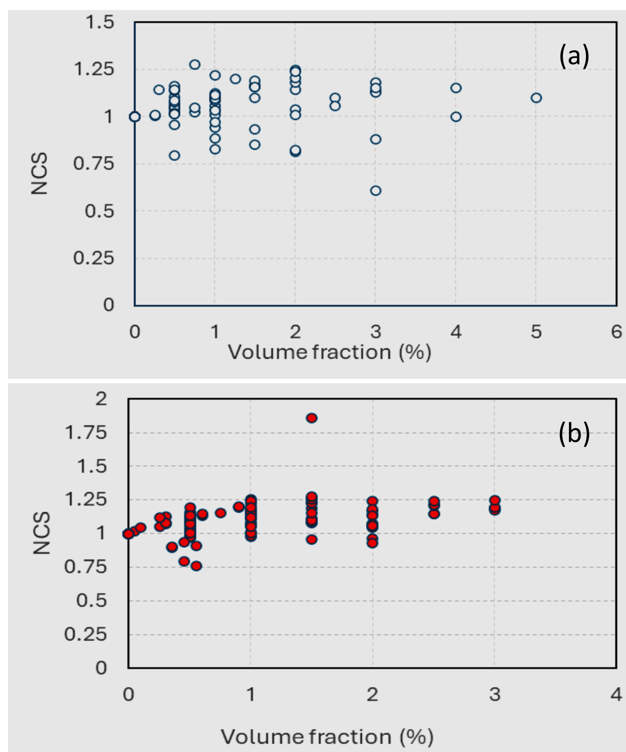


**Figure 5.** Normalized compressive strength for SFRC produced from (a) normal strength concrete and (b) high strength concrete.

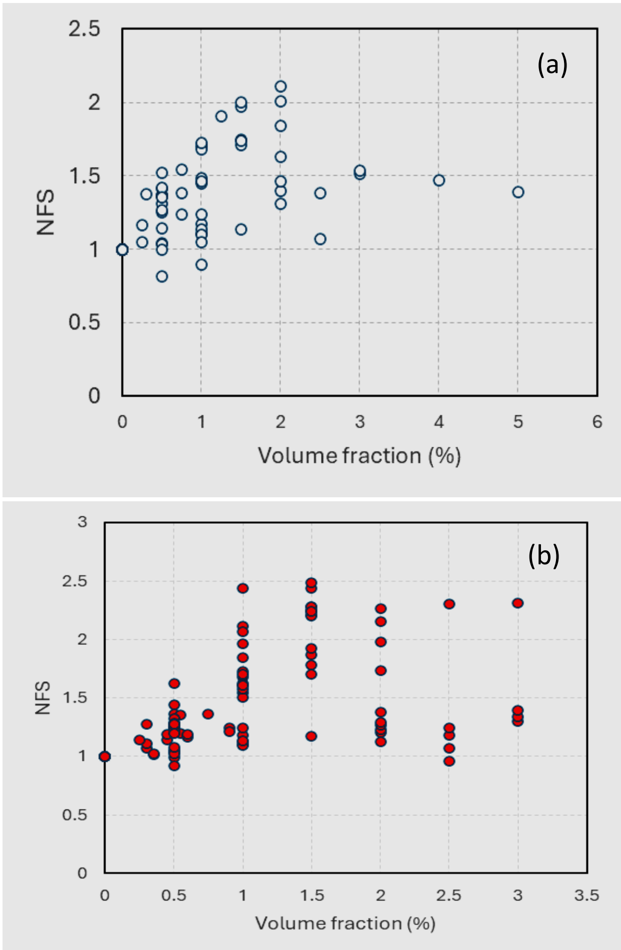


**Figure 6.** Normalized flexural strength for SFRC produced from (a) normal strength concrete and (b) high strength concrete.

***Influence of concrete grade on the flexural strength of SFRCs***

Figure 6(a) and Figure 6(b) present the comparison and contrast between the normalized flexural strength of the NSC and HSC in terms of the volume fractions. NSC exhibited an average of 13.87% improvement in the normalized flexural strength with only 5.88% failure (i.e. below the flexural strength of the corresponding control concrete). The HSC, on the other hand, produced a 43.93% increase with only 3.03% of the tested samples below the control threshold values. This has further shown that HSC had 26.4% improvement in strength and additional 21.4% samples crossing the flexural strength threshold over the NSC for similar volume fractions.

***Influence of concrete grade on the split tensile strength of SFRCs***

Steel fibre reinforced NSC provided 18.80% increase in the tensile strength where not less than 75.38% of the tested samples crossed the tensile strength threshold for control concretes. Conversely, steel fibres in HSC performed slightly better with 21.22% improvement in tensile strength with 86.6% of the samples crossing the tensile strength threshold. These results show that HSC had 2.03% improvement in strength and additional 14.9% samples crossing the tensile strength threshold over the corresponding NSC for similar volume fractions. Based on the increase in the average NTS and the success rate, it can be concluded that HSC offers a better enhancement of split tensile strength compared to NSC. Figure 7(a) and Figure 7 (b) present the comparison and contrast between the normalized split tensile strength of the NSC and HSC in terms of the volume fractions.

Figure 8 presents the summary of the performance of SFRC produced from both normal- and high-strength concretes as a measure of the success ratings and strength enhancement in terms of the compressive, flexural and tensile strength. It is noteworthy that this improvement does not match the cost of producing the high strength concrete.

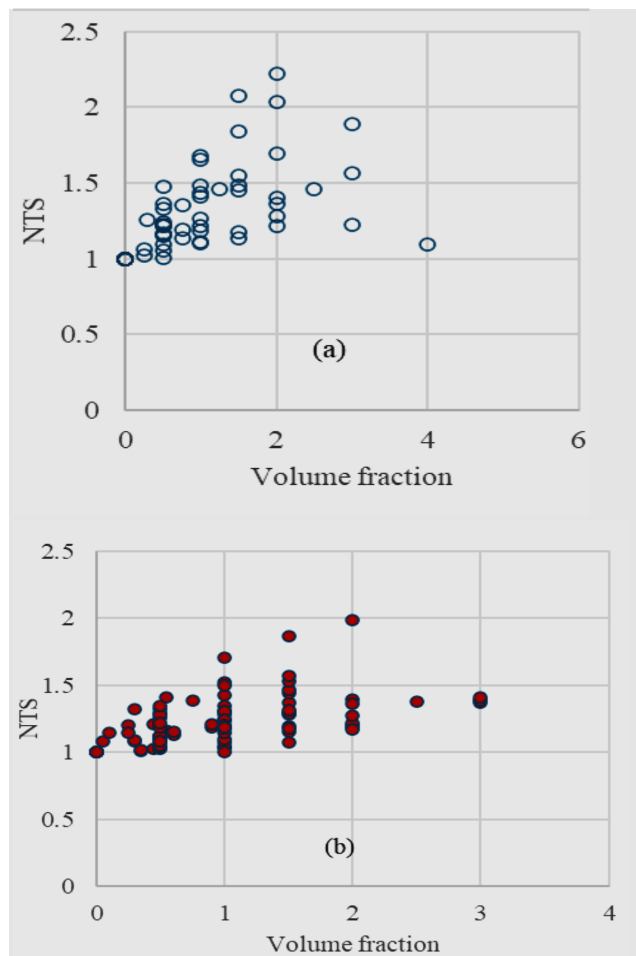


**Figure 7.** Normalized split tensile strength for SFRC produced from (a) normal strength concrete and (b) high strength concrete.

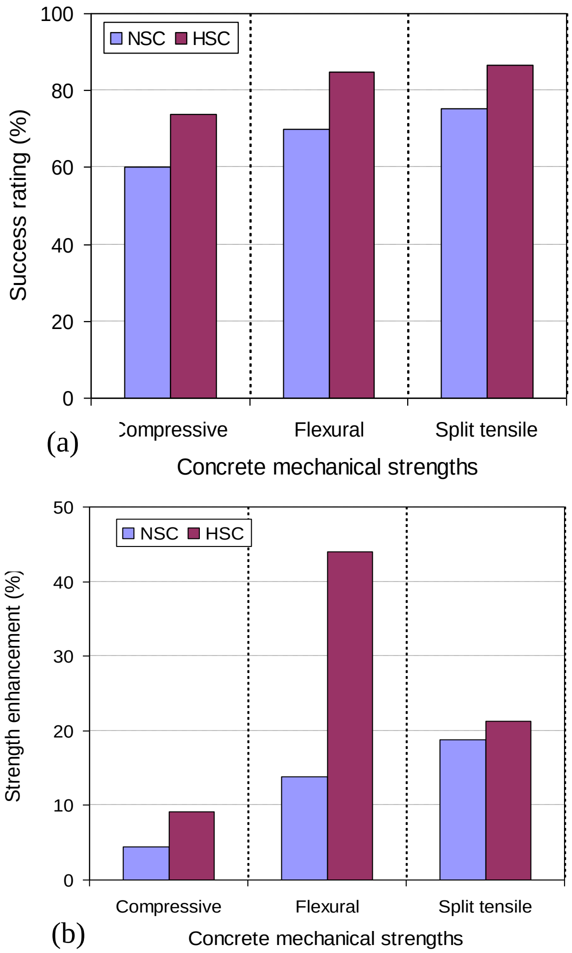


**Figure 8.** Performance of SFRC produced from NSC and HSC in terms of (a) success ratings and (b) strength enhancement.

## CONCLUSION

The influence of critical factors like fibre content, length, diameter, and volume fraction on the performance of steel fibre reinforced concretes (SFRC) for both the normal- and high-strength concrete is presented in this paper. Statistical analysis was made from 209 experimental database of SFRC, 82% of which were produced from hooked steel fibres. The following conclusion can be drawn from the study.

The incorporation of steel fibres into concrete led to an increase in all three strengths. The optimal volume fraction was 1.5% for compressive and flexural capacity, and 2.0% for tensile strength.

The length of the steel fibre has a direct influence on the performance of steel FRC. The optimum length was between 30 to 60 mm for compressive and tensile strengths, while the flexural strength was maximum at an optimum length of 50 mm.

The diameter of the fibre had been found to affect the mechanical properties of SFRC. The optimum diameter of fibre were 0.5 mm, 0.55 mm and 0.62 mm for compressive, tensile and flexural strength, respectively.

High-strength concrete had better influence on the performance of steel FRC than the normal-strength concrete in terms of the success ratings and the mechanical strengths. However, the strength and performance enhancement do not significantly match the cost of production of HSC-based FRC.

## DECLARATIONS

### Corresponding Author

Correspondence and requests for materials should be addressed to AdewuyiA@ub.ac.bw; ORCID: 0000-0001-8190-7357. The ORCID for Odette Animbom: 0009-0009-1530-8714.

### Data availability

The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

### Acknowledgements

The authors would like to acknowledge the technical staff of the Structural Engineering Laboratory of the Department of Civil Engineering for their support and for creating a conducive environment to conduct this research.

### Authors' contribution

A.P. Adewuyi developed the research idea, identified the research gaps in the body of knowledge and concrete technology in practice, designed data extraction processes, contributed to data analysis, interpreted the results and revised the manuscript. O. Animbom presented the proposal, analyzed data, interpreted the results and wrote the manuscript under the supervision and guidance of A.P. Adewuyi. Both authors read and approved the final manuscript.

### Competing interests

The authors declare no competing interests in this research and publication.

## REFERENCES

Adewuyi, A. P., Otukoya, A. A., Olaniyi, O. A. & Olafusi, O. S. (2015). Comparative studies of steel, bamboo and rattan as reinforcing bars in concrete: tensile and flexural characteristics. *Open Journal of Civil Engineering*, 5(2), 228-238. https://doi.org/10.4236/ojce.2015.52023

Ali, A. M., Falah, M. W., Hafedh, A. A., Al-Khafaji, Z. S., & Radhi, S. (2022). Evaluation the influence of steel-fiber on the concrete characteristics. *Periodicals of Engineering and Natural Sciences*, *10*(3), Article 3. https://doi.org/10.21533/pen.v10i3.3111

Balagopal, V., Panicker, A. S., Arathy, M. S., Sandeep, S., & Pillai, S. K. (2022). Influence of fibers on the mechanical properties of cementitious composites—A review. *Materials Today: Proceedings*, *65*, 1846–1850. https://doi.org/10.1016/j.matpr.2022.05.023

Jun, H., Seo, D. J., Lim, D. Y., Park, J. G., & Heo, G. (2023, March 9). Effect of Carbon and Steel Fibers on the Strength Properties and Electrical Conductivity of Fiber-Reinforced Cement Mortar. Applied Sciences. https://doi.org/10.3390/app13063522

Kim, S., Kim, D.J., Kim, S.-W., Park, C. (2019). Tensile behavior characteristics of high-performance slurry-infiltrated fiber-reinforced cementitious composite with respect to fiber volume fraction. Materials, 12(20), 3335. https://doi.org/10.3390/ma12203335

Rizzuti, L., & Bencardino, F. (2014). Effects of fibre volume fraction on the compressive and flexural experimental behaviour of SFRC. *Contemporary Engineering Sciences*, *7*, 379–390. https://doi.org/10.12988/ces.2014.4218

Sidiq, A., Gravina, R., & Giustozzi, F. (2019). Is concrete healing really efficient? A review. *Construction and Building Materials*, *205*, 257–273. https://doi.org/10.1016/j.conbuildmat.2019.02.002

Zhang, L., Zhao, J., Fan, C., & Wang, Z. (2020). Effect of Surface Shape and Content of Steel Fiber on Mechanical Properties of Concrete. *Advances in Civil Engineering*, *2020*, 1–11. https://doi.org/10.1155/2020/8834507

Zhang, X. X., Abd Elazim, A. M., Ruiz, G., & Yu, R. C. (2014). Fracture behaviour of steel fibre-reinforced concrete at a wide range of loading rates. *International Journal of Impact Engineering*, *71*, 89–96. https://doi.org/10.1016/j.ijimpeng.2014.04.009