

CRANFIELD UNIVERSITY

HAMAD KHALEL

ENHANCING MECHANICAL PROPERTIES OF CONCRETE
MATERIAL WITH FIBRES OF DIFFERENT MATERIALS

SCHOOL OF AEROSPACE, TRANSPORT AND
MANUFACTURING

PhD in Civil Engineering

PhD

Academic Year: 2019 - 2022

Supervisor: Dr Muhammad Khan
Associate Supervisor: Prof. Andrew Starr
December 2022

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Supervisor: Dr Muhammad Khan
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This thesis is submitted in partial fulfilment of the requirements for
the degree of PhD

***(NB. This section can be removed if the award of the degree is
based solely on examination of the thesis)***

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ABSTRACT

Fibre reinforced cementitious composites are highly effective for construction due to their enhanced concrete properties. Materials such as steel fibre have been used extensively to reinforce concrete because of their excellent mechanical properties. Academic researchers have comprehensively discussed the impact and challenges of fibre reinforcement to obtain optimal properties in the resultant concrete. Most researchers have reported the mechanical performance of fibre-reinforced concrete (FRC) under static loads. Concrete with fibre reinforcement is stronger and more ductile than concrete without reinforcement. Significant efforts have been made to demonstrate the properties and enhancements of concrete after reinforcing it with different types and shapes of fibres. However, the optimization in the reinforcement process is still unanswered. No academic study in the literature now available can pinpoint the ideal fibre type, quantity, shape, and, more crucially, the overall technical viability of the reinforcement. After performing the optimization, researchers considered how these optimizations could affect the crack resistance or properties under dynamic loads with different temperatures. However, a comprehensive analysis is still missing that can explain the crack resistance performance of FRC under dynamic loads at relatively high temperatures. The main aim of this thesis is to investigate the mechanical behaviour of concrete structures under thermo-mechanical dynamic loads about reinforcing fibres of different weight ratios. This study uses parametric analysis in accordance with extensive mechanical tests to identify the optimal shape, size, and percentage of fibres. The design variables for optimization are divided into input and output parameters. The input parameters are the influences of the type, length, and percentage of fibres on concrete performance, including samples of fresh and mechanical concrete properties, to search for the most effective relation of fibre dose and dimension to optimize the combined responses of workability, splitting tensile strength, flexural strength, and compressive strength. The current work also proposes the Khan Khalel model, which can predict the desirable compressive and flexural strengths for any given values of key fibre parameters. Statistical tools are used to develop and validate the model with numerical results. The proposed model is easy to use but

predicts compressive and flexural strengths with errors under 6% and 15%, respectively. This error primarily represents the assumption made for the input of fibre material during model development. It is based on the elastic modulus of the material and hence neglects the plastic behaviour of the fibre. A possible modification in the model for considering the plastic behaviour of fibre will be considered as future work. Finally, this study analyses the efficacy of FRC beams for crack resistance under coupled loads, i.e., dynamic loads at relatively high temperatures. Cantilever FRC beams are tested on a modal exciter in a band heater to expose the beams to bending loads at different temperature values. The variation in the dynamic response parameters of the beam, including modal amplitude and frequency, is discussed and compared with experimental results for regular and reinforced concrete beams. The stress intensity factor and displacement amplitude characteristics show that the steel FRC specimens have excellent ductile behaviour and higher crack resistance than ordinary concrete samples.

Keywords:

Concrete, Steel fiber, plastic fiber .waste materials ,mechanical properties ,dynamic response ,Thermo-mechanical loads, optimization

ACKNOWLEDGEMENTS

The work presented in this thesis was completed at Cranfield University between June 2019 and December 2022 while I was a full-time PhD student. Allah Almighty deserves all praise and thanks for making this a reality. Sincere appreciation to Dr Muhammad Khan, my first supervisor, for his help during the period of my research. Your constant encouragement and thoughtful comments will never be forgotten. Thank you for making your office available despite your hectic schedule. I appreciate the numerous changes you made to the papers that led to this thesis and the fresh suggestions you always provided, notably for your useful corrections to the shared articles. Prof. Andrew Starr was a member of the team of co-supervisors I had at various phases of my project. In addition, I appreciate and thank my sponsor, the Ministry of Higher Education and Research of Libya, and the cultural affairs attaché office of the Libyan embassy in London for providing me with this scholarship. Finally, my gratitude is extended to my father's spirit, who constantly encouraged me to continue my studies.

I want to thank my family for their support, understanding, and patience throughout the duration of this study; in particular, I'd like to thank my wife, Widad, and our three wonderful children, Hasan, Wasan, and Worood. Your pleasure and affection have sustained me throughout the past four years of happiness and sorrow. In addition, I thank my mother, siblings, and sisters. Their prayers and faith have motivated and inspired me to pursue this research. Furthermore, my appreciation for my brothers Zedan and Abd El Basset is immeasurable. Lastly, I would like to thank my friends and colleagues at Cranfield University for the time they have contributed to my research over the previous few years. I am grateful to everyone who, in one way or another, contributed to the success of my research.

LIST OF PUBLICATION

- 1) Khalel, H., Khan, M., Starr, A., Khan, K. A., & Muhammad, A. (2021). Performance of engineered fibre reinforced concrete (EFRC) under different load regimes: A review. *Construction and Building Materials*, 306, 124692.
- 2) Khalel, H., Khan, M (2020). Effects of reinforced fibres on mechanical and crack resistance properties of structural concrete. The Secretariat of the 74th RILEM Week and 40th Cement & Concrete Science Conference University of Sheffield, UK.
- 3) Khalel, H., Khan, M (2022), Parametric Study for Optimizing Fibre Reinforced Concrete Properties. (Under Review).
- 4) Khalel, H., Khan, M. Modelling fibre-reinforced concrete for predicting optimal mechanical properties. (Under Review).
- 5) Khalel, H., Khan, M., Starr, A. Dynamic response-based crack resistance analysis of fibre reinforced concrete beams under different temperatures and crack depths. (Under Review).

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LIST OF ABBREVIATIONS

BPO	Benzoyl Peroxide
BF	Basalt fibre
BF	Basalt fibre
CFRP	Carbon Fibre Reinforced Polymer
EFRC	Engineered Fibre Reinforced Concrete
ESF	Engineering Steel Fibre
FRC	Fibre Reinforced Concrete
FRP	Fibre Reinforced Polymer
HSC	High-Strength Concrete
ISF	Industrial Steel Fibre
PC	Polymer Concrete
PET	Polyethylene Terephthalate
PFRC	Polymer Fibre Reinforced Concrete
PP	Polypropylene
RAC	Recycled Aggregate Concrete
RSF	Recycled Steel Fibre
SCC	Self-Compacting Concrete
SF	Steel Fibre
SSF	Short Straight Fibres
HF	Hooked Fibre
LSF	Long Straight Fibre
SFRC	Steel Fibre Reinforced Concrete
SFRCAC	Steel Fibre Reinforced-Recycled Coarse Aggregate Concrete
SRAC	Steel Fibre Recycled Aggregate Concrete
UHPC	Ultra-High-Performance Concrete
UHP-FRC	Ultra-High Performance Fibre Reinforced Concrete
WPF	Waste Plastic Fibres

UHPCC	Ultra-High Performance Cementitious Composites
CRF	Crumb Rubber Fibre
CW	Caco3 Whisker
RSM	Response Surface Method.
OPC	Ordinary Portland Cement
PVA	Polyvinyl Alcohol Fibre
HFRC	High-Performance Hybrid Fibre Reinforced Concrete
SPHFRC	Steel-Polypropylene Hybrid Fibre Reinforced Concrete
SFRC-1	Steel Fibre Reinforced Concrete (Straight): Novocon® XR-1050
SFRC-2	Steel Fibre Reinforced Concrete (Crimped): Novocon® FE-1050
PFRC-1	Plastic Fibre Reinforced Concrete (Macro/ Monofilament): Enduro® Mirage
PFRC-2	Plastic Fibre Reinforced Concrete (Crimped): Enduro®Fiber High-Performance Polymer (HPP)
ANN	Artificial neural network
IST	Inter-face shear transfer
SIF	Stress intensity factor

NOMENCLATURE

$\varepsilon^{el}, \varepsilon^{pl}$	Elastic and plastic strains.
d_c, d_t	Uniaxial compressive and tensile damage variables.
σ_{ij}	Function of stress state
D_{ijkl}^{el}	Initial elasticity matrix
$\varepsilon_{ij}, \varepsilon_{ij}^{pn}$	Total and plastic strain tensor, respectively
$\bar{q}$	Mises equivalent effective stress
$\bar{p}$	Hydrostatic stress
$\bar{\sigma}_{max}$	Maximum principal effective stress
σ_{c0}, σ_{t0}	Uniaxial compressive and tensile stresses
σ_{b0}	Equiaxial compressive yield stress
K_c	Ratio of second stress invariant on the tensile meridian to that on the compressive one
ψ	Dilation angle
e	Eccentricity that defines the rate at which the function approaches the asymptote
G	Potential flow function
E_0	Elastic modulus
(C.S)	Compressive strength
(F.S)	Flexural strength
a	Crack depth
A	Beam section
A_L, A_R	Coefficients
b	Beam width
B	Coefficient
B_L, B_R	Coefficients
C_L, C_R	Coefficients
D_L, D_R	Coefficients
E	Elastic modulus

E_0	Elastic modulus at T_0
f	Frequency
$f_r(a/H)$	Shape function
H	Beam thickness
I	Area moment of inertia
J_z	Momentum of inertia
k	Torsional spring stiffness
l	Distance between the crack location and fixed end of the beam
L	Beam length
m	End mass
m_{acc}	Accelerometer mass
ω	Angular frequency
ω_s	Angular frequency of a shaker
$q_n(t)$	Modal coordinate of the n-th mode
ρ	Density
t	Time
$T(t)$	Modal coordinate
U_0	Shaker displacement amplitude
x	Distance to the fixed end of the beam
$y(x, t)$	Beam displacement due to bending
$y_L(x, t)$	Fixed-end side beam displacement
$y_R(x, t)$	Free-end side beam displacement
$Y(x, t)$	Mode shape of the beam
$Y_n(x)$	n-th mode shape of the beam

1 INTRODUCTION

1.1 Research Background

Concrete is the most utilized human-made material in the world. Concrete is a mix of cement, aggregate, and water and is an essential composite material that is universally used in the construction industry due to its flexibility in terms of shape, compressive strength, and excellent heat-resistance properties. It gives further durability of construction with a high level of mechanical strength. However, along with these favourable construction properties, concrete also has limitations. One of the most prominent is the brittle nature of failure without any significant plasticity. It is also weak under tensile loads. To overcome these limitations, an idea was raised to reinforce concrete with other constituents, such as steel, plastic, and waste materials, to achieve the desired construction properties.

The use of fibre in concrete started in the mid-1960s. The main aim of using fibre was to modify the mechanical properties of concrete to make it suitable for forming structures. Much effort has been made to reinforce concrete with different types of fibres. However, various unaddressed challenges related to the optimization of the fibre proportion, the shape of the fibres, mixing methods, and the properties obtained demand comprehensive research. Many articles have complied with past research efforts in optimizing the use of fibre, whereby the properties are mainly tested under quasi-static conditions. Previously, researchers used fibres from various materials and reported their findings. For example, crumb rubber was added to concrete for reinforcement. The rubber had a negative impact on the mechanical properties of the resulting concrete, although the crack-resistance properties were increased at the same time. The researchers later added steel fibres to the same mix and discovered a positive impact on the overall energy absorption of the resulting concrete.

1.2 Research Problem

Most researchers have reported the mechanical performance of fibre-reinforced concrete (FRC) under static loads. Concrete reinforced with fibres is stronger and

more ductile than concrete without reinforcement. Numerous efforts have been made to demonstrate the properties and enhancements of concrete after reinforcing it with fibres of various types and shapes. However, the question of optimization in the reinforcement process remains unsolved. No academic study currently available in the literature can pinpoint the ideal fibre type, amount, shape, and, more notably, the overall technical viability of the reinforcement. Following optimization, researchers considered how these optimizations might affect crack resistance or properties under dynamic loads at various temperatures. However, a comprehensive analysis that can explain the crack resistance performance of FRC under dynamic loads at relatively high temperatures is still lacking. Fibre reinforced concrete (FRC) construction applications experience fatigue and failure during their service life. Temperatures, mechanical loads, load cycles, workplace conditions, and crack initiation and propagation are among the factors that play a role in this failure. As major failure is expensive, researchers believe early detection is the best means of avoiding catastrophic damage. Furthermore, concrete structures such as bridges are costly and challenging to replace rather than repair. The possibility of structural fatigue increases with prolonged thermo-mechanical cyclic stress. Fatigue damage causes structural cracks and, eventually, catastrophic failure. As a result, investigating structural damage during the construction life cycle is critical. The structural dynamic response accurately reflects structural performance and the structure's real-time coupled loads also have an influence. Furthermore, even while a concrete structure is still operational, the dynamic response can be easily measured in situ. The effectiveness of measuring the dynamic response of FRC to estimate structural performance under applied thermo-mechanical loads is investigated in this thesis.

1.3 Research Aim and Objectives

The fundamental aim of this study is to investigate the mechanical behaviour of concrete structures under thermo-mechanical dynamic loads in the presence of reinforcing fibres with different weight ratios. The research has the following objectives.

- 1) To review the effect of fibres, including steel, plastic, and waste materials, on concrete performance.
- 2) Optimisation of reinforced fibres in concrete.
- 3) To validate the optimization by testing a concrete structure under conventional quasi-static loads.
- 4) To create an empirical model of the impact of reinforcing fibres on concrete mechanical behaviour and validation.
- 5) To investigate the impact of fibres on the mechanical behaviour of concrete under thermo-mechanical dynamic loads.

1.4 Research Methodology

The research methodology was composed of four steps, in order to achieve the research, aim and objectives referred to above.

- 1) The initial step paid particular attention to contextual understanding and comprehending the literature. A comprehensive literature review was conducted. The impact of different fibre types on concrete and the key conclusions and gaps in FRC research were highlighted with a critical analysis of the existing literature. This achieved research objective 1 above.
- 2) An empirical laboratory mixture was used to reinforce concrete with different fibres. Fresh and quasi-static tests were performed to investigate optimization in terms of the type, ratio, and shape of the fibres. These tests investigated the workability and the tensile, compressive, and flexural properties after the reinforcement. Data analysis was performed to correlate quasi-static properties and determine the optimal fibre type, ratio, and shape. This achieved research objectives 2 and 3.
- 3) The optimized reinforcement parameters were used to develop cantilever beam specimens for dynamic thermo-mechanical load tests. A modal exciter-based experimental scheme was developed to test the mechanical behaviour of the reinforced concrete beam specimens. The data in respect of crack growth, optimized reinforcement parameters, and applied coupled

loads were mathematically correlated and a model was developed for further validation. This achieved research objective 4.

- 4) The final phase was the validation of the developed model under objective 4. Specimens were tested on arbitrary values of thermo-mechanical loads. Values obtained from the model and experiments were compared and the errors measured. Further model modification was performed in the case that the error was not within acceptable limits. This achieved research objective 5.

1.5 Structure of the Thesis

This thesis contains seven chapters. Figure 1-1 provides readers with an overview of the organization of the thesis and a sense of how the chapters are linked. This is followed by a summary of the content of the thesis chapters.

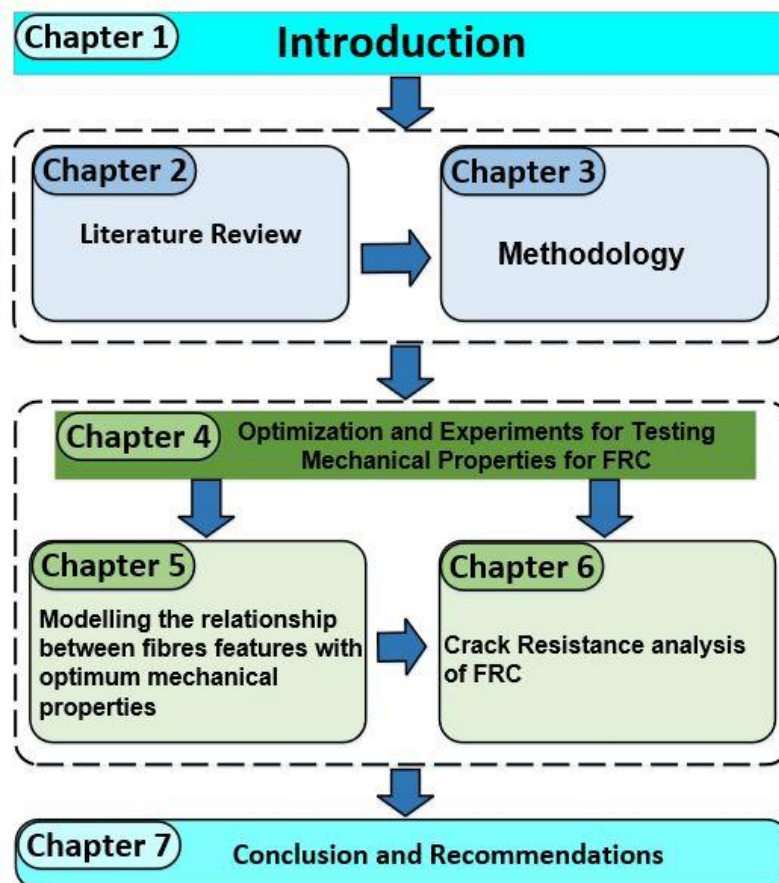


Figure 1-1 Structure of the thesis.

Chapter 2: Literature Review. This chapter presents a critical analysis of previous research studies emphasizing the optimization of FRC to improve its resistance to various load regimes, with a particular emphasis on coupled load conditions. The preamble provides the historical context, a description of the evolution of concrete as a material for advanced structures, such as multi-storey buildings, dams, bridges, industrial structures, retaining walls, and hydraulic and marine structures, and the basic principles of concrete production. A discussion of FRC, such as fibre types and shapes, mixing techniques, and property testing, is then presented. A separate section outlines how the mixing of fibres can influence fatigue and fracture behaviour, particularly under varying load regimes. Gaps in the existing research, with possible new directions for investigation, are discussed in the conclusion to the chapter.

Chapter 3: Methodology. This chapter provides an overview of the techniques that were utilized throughout the remainder of the research for this thesis. Various applications of FRC in construction are examined in terms of the methods described.

Chapter 4: Optimization and Experiments for Testing the Mechanical Properties of FRC. This chapter presents the parametric analysis conducted to identify the optimal shape, size, and percentage of fibres for the reinforcement of concrete. The design variables for optimization are divided into the input and output parameters. The input parameters are the influences of the type, length, and percentage of fibres on concrete performance, including samples of fresh and mechanical concrete properties.

Chapter 5: Modelling the Relationship between Fibre Features with Optimum Mechanical Properties. This chapter proposes the Khan Khalel model, which can predict the desirable compressive and flexural strengths for any given values of key fibre parameters. Statistical tools were used to develop and validate the model and the numerical results are presented in the chapter.

Chapter 6: Crack Resistance Analysis of FRC. This chapter presents the results of analysing the efficacy of FRC beams in terms of their crack resistance under coupled loads, i.e., the dynamic load at relatively high temperatures. Cantilever

FRC beams were tested on a modal exciter in a band heater to expose the beams to bending loads at different temperature values. The variation in the dynamic response parameters of the beams, including modal amplitude and frequency, is discussed, and compared with experimental results for regular and reinforced concrete beams.

Chapter 7: Conclusion and Future Investigation. This chapter summarizes the findings from the research conducted for this thesis. Before discussing the significant contributions of this thesis, a discussion is presented of the research topics established in Chapter 1. After a summary of the achievements of the research, the chapter provides suggestions for future applications of the work presented in this thesis. Lastly, several potential directions for improvement are given for future work.

2 LITERATURE REVIEW

2.1 Introduction

The mixing of fibres in concrete began in the mid-1960s to improve its mechanical properties and the construction of structures [1–5]. Since then, considerable effort has been expended to demonstrate the success of concrete reinforcement with different types of fibres [5]. However, a number of reinforcement optimization issues are still unaddressed, such as justification of a suitable fibre material, shape and proportion, technical feasibility of the mixing method and criteria to quantify the desired resultant properties; each of which requires comprehensive research [6]. The majority of the articles published have reported the performance of concrete structures under quasi-static conditions [5,7]. The performance investigations mainly involve tensile, compressive, and flexural strength estimations of the reinforced structure. In tensile and compressive performance tests, applied quasi-static force is plotted against the deformation observed in the structure; while in the flexural case, the former is plotted against mid-structural deflection, as shown in Figure 2-1 [8–10]. However, real concrete structures normally do not have ideal quasi-static load conditions and experience load changes with respect to time, which are termed dynamic load conditions. Moreover, in real applications, these changes in applied mechanical loads are coupled with thermal loads, as structures are mainly exposed to the outside environment during their working life [7,11–13].

Extensive review articles have been published describing investigations to evaluate the performance of fibre reinforced concrete (FRC). The descriptions in the review articles demonstrate the significance and limitations of previous investigations without a particular emphasis on the issues of reinforcement optimization and structural performance following reinforcement against real-world loads, such as coupled loads. This chapter presents a critical analysis that compiles previous research studies with an emphasis on the optimization of RFC to enhance its strength against different load regimes, with a particular focus on coupled load conditions. The historical background, a description of the evolution of concrete as a material for advanced structures such as multi-storey buildings,

dams, bridges, industrial structures, retaining walls, and hydraulic and marine structures, and the fundamental principles of concrete production are provided as a preamble. Later, a discussion of FRC, fibre types and shapes, mixing methods and testing of properties is provided. A separate section describes how fibre mixing can affect fatigue and fracture behaviour, especially under different load regimes. Gaps in the existing research with possible new directions are discussed in the conclusion. In the published academic literature, little attention has been given to the performance estimations of concrete structures under coupled loads. It can be anticipated that the mentioned unresolved issues in fibre reinforcement will end in a complex zone of empirical results if the chosen structures are tested under coupled load conditions.

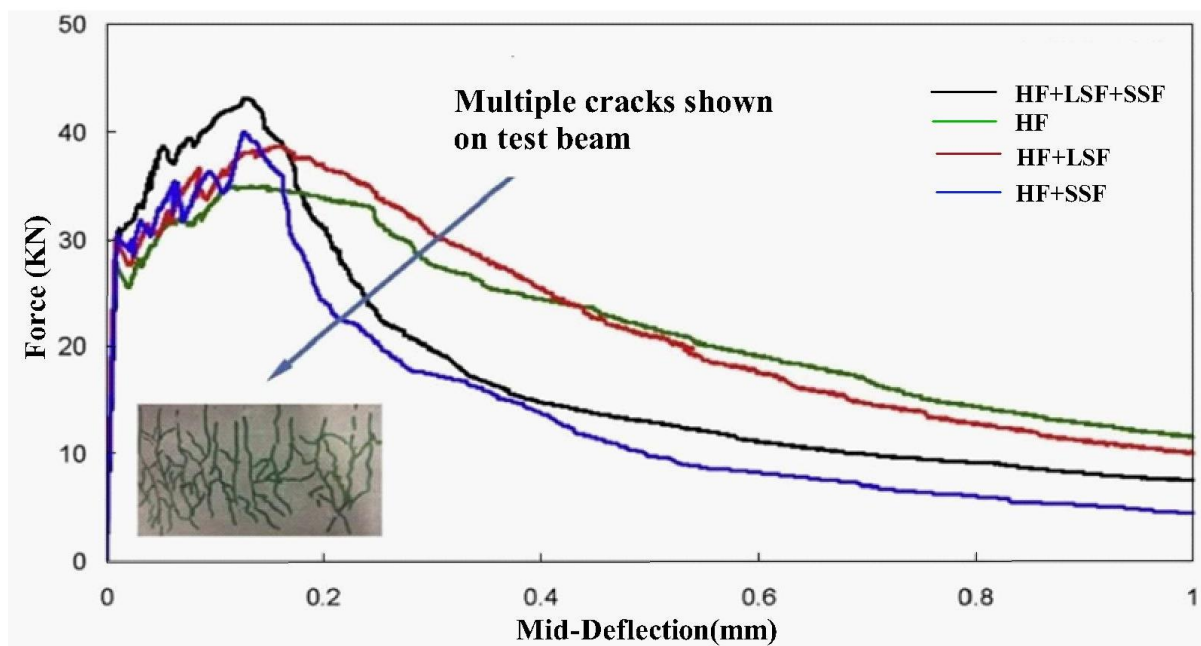


Figure 2-1 Impact of different type of FRC on the flexural behaviour of concrete[9].

2.2 Historical Background of Engineered FRC

Concrete as a material of construction is widely adopted because it is economical and able to withstand the varied environmental conditions [14]. The Egyptians and the Romans both used concrete, but with the break-up and downfall of the Roman Empire, many of its technological secrets were lost, and the modern history of concrete extends for only two centuries. In 1824, Portland cement was

patented, which later proved to be the most important concrete construction material [15,16]. Today, concrete is regarded as one of the most considerable and universal materials in building construction because of its ability to withstand compressive stress, its heat resistance, durability and enormous flexibility of shape [17]. Concrete is classified as a quasi-brittle material, and there are many small deformations before failure [18]. It works well under compression, but not as well against tensile loads. Published research indicates that concrete has relatively low flexural strength compared with compressive forces. The requirement to enhance tensile and flexural strengths led researchers to investigate materials that can be mixed with traditional concrete ingredients without a significant impact on other desired properties.

In the past, researchers investigated the extent to which the fibres of materials with good tensile properties could be used to reinforce concrete to obtain the required enhancement [5,17]. Figure 2-2 shows the impact of polypropylene (PP) fibre reinforcement on the mechanical properties of concrete, whereby tensile and flexural strengths are significantly increased without any negative influence on compressive strength at the highest percentage of fibre volume (0.3%).

Design Guide AC1 544.4R issued by the American Concrete Organization specifies FRC “as concrete including separated randomly adapted fibres”[19]. Since the 1960s, extensive research has been carried out on FRC [20], beginning when Romualdi and Batson issued their empirical results regarding enhanced mechanical properties [21]. In addition to mechanical properties, fresh properties, such as workability and flow, have been investigated by researchers and their test results were used to enhance older construction codes for structural materials [22–24].

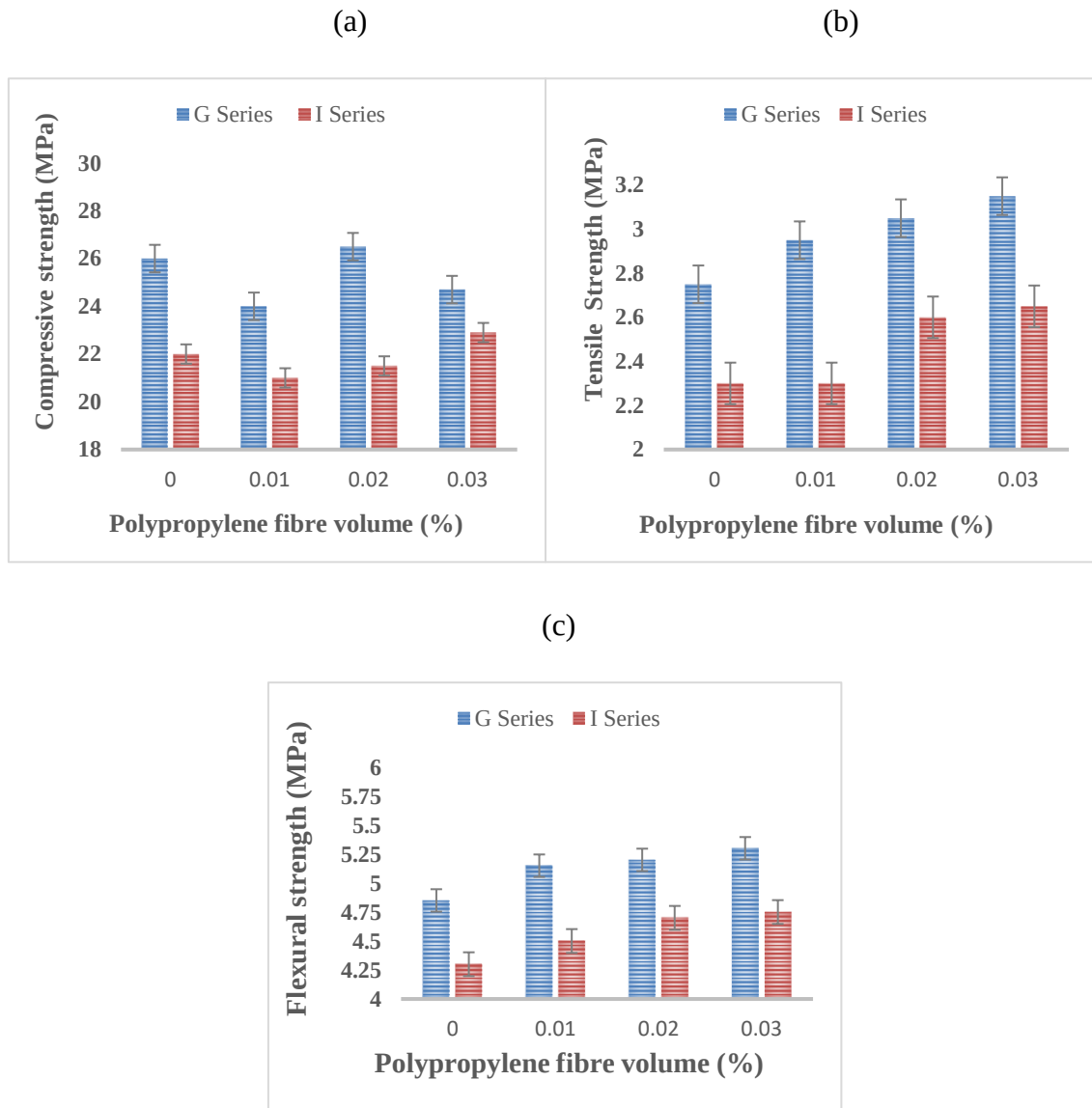


Figure 2-2 Effect of fibre on mechanical properties of concrete [5]. (a) Compressive strength of FRC; (b) tensile strength of FRC, (c) flexural strength of FRC.

Fresh concrete properties are mainly influenced by fibre material. According to GangaRao et al., the workability and strength of concrete can be enhanced if polymer can be used a fibre material with different admixtures [25]. Using the correct fibres in the correct mix can greatly increase the tensile strength of FRC. However, the final product may not always be appropriate for use in building applications due to the reduced workability of the concrete. Such concrete will be

difficult to use due to the phenomenon of honeycombing [26]. It is more often the case, that as fibre is large in quantity, it can sharply reduce workability [27]. The use of FRC should be confined to those applications in which any decrease in splitting strength and crack dissemination is not significant, and where a mix of fibres and reinforcing bars could produce a synergistic outcome [28].

2.3 Evolution in Concrete Materials for Advanced Structures

A multiscale structure, ranging from the macro- to the micro-scale of the traditional aggregate concrete structure, is shown in Figure 2-3. Typically, macro-level structures are considered for characterizing material behaviour. However, information at the multilevel, such as the meso level and micro scale, is also needed to have a concurrent multiscale model and accurate predictions of macroscopic properties. Conventional concrete structures are brittle in nature and continuous efforts have been made in the past to reinforce them with different types of fibre [29].

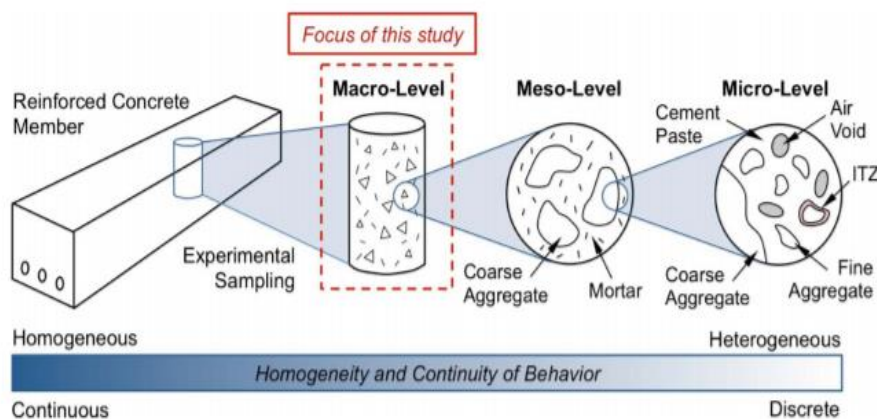


Figure 2-3 Scales of concrete adapted from [29].

In one study, a concrete beam reinforced with polymer fibre (polymer FRC [PFRC]) showed an increase in strength and stiffness when compared with a traditional concrete beam formed by mixing aggregate, water, and Portland cement[30]. The observed improvements in the brittle mode of concrete were not only due to the characteristics of the fundamental materials, but also because of their relative proportions, dimensions and crosswise arrangements [31–33]. According to previous research, fibres in concrete lead to durability, fire

resistance and endurance against thermal stress. It is easy to use and, for this reason, has attracted the attention of the construction industry in gaining economic benefits [34–38]. The concrete used in construction projects is reinforced with steel or macro synthetic fibres, which leads to exceptional material properties [39–42]. The addition of fibres in a concrete mix can reduce crack initiation and propagation. Fibres also offer greater flexibility in structures against crack propagation due to split obstruction and hence elongate the time to catastrophic fracture and enhance the mechanical properties of concrete [43]. It has been demonstrated that the presence of fibres not only influences concrete crack resistance, but also improves other properties [44]. The reason for this improvement is mainly due to the reduction of CO₂ and water content, as the fibres proportionally replace the amount of aggregate and cement [45,46]. Randl et al. investigated the flexural strength of ultra-high performance concrete (UHPC) beams reinforced with small volumes of fibre, and reported that adding high-grade steel fibres (2% by volume) gave an overall increase in load-bearing capacity of about 15% [47]. Other researchers observed that plastic fibres increased compressive strength and ductility [48,49], and Liu et al. demonstrated that the tensile strength of concrete improved by increasing the amount of steel fibre [50].

In addition to the investigations referred to above, several other significant research contributions have demonstrated the influence of fibres on concrete properties, as shown in Table 2-1. The majority of studies investigated the effect of fibre reinforcement on the fresh and mechanical properties of concrete. However, these investigations did not consider the influence of shape, type, and amount of fibre during reinforcement. In the majority of the studies, ideal or lab-based loading conditions were used to determine the resultant properties. Very little effort has been made to investigate the performance behaviour of a reinforced structure under realistic loading conditions, such as coupled thermo-mechanical loads.

Table 2-1 Evolution of FRC.

Authors	Years	Contribution to knowledge	Limitations
Henager et al. [1-5]	1983 1984 1988 2009 2011	The mixing of fibres in concrete began in the mid-1980s to improve its mechanical properties and the construction of structures.	a number of reinforcement optimization issues are still unaddressed, such as justification of a suitable fibre material, shape and proportion, technical feasibility of the mixing method and criteria to quantify the desired resultant properties; each of which requires comprehensive research.
Aldahdooh et al. [6]	2013	This article examined the Evaluation of ultra-high-performance-fiber reinforced concrete binder content using the response surface method.	The results showed that the prediction by using RSM was adequate to adjust the quantity of OPC and SF in the production of the material of UHP-FRC. Those values have to be further reduced.
Wille et al. [26]	2014	This paper investigated the stain hardening properties of ultra-high-performance FRC (UHP-FRC) under direct tensile loading.	The study was restricted to the tensile performance of small samples. They researchers recommended using large samples for future study to adopt their properties for specific practical applications.
Li et al. [27]	2016	This study examined the impact of superplasticizers on the fresh properties of concrete.	The use of coarse aggregate reduced compressive and tensile strengths.
Aslani et al. [28]	2019	The study investigated the effects of adding two types of fibre (i.e., steel and polypropylene) on workability and concrete hardening.	Proposed mixture of fibres and recycled aggregate self-compacting concrete was found to be suitable for only a few limited designs of concrete structure.
Long et al. [38]	2019	This paper investigated the impact of using cement-soil reinforced by coal gangue on mechanical and durability of foundations.	A mass loss of the resultant reinforcement was observed for a value of 4–7% of the original material due to the use of acidic immersion.
Sanjeewa et al. [51]	2017	This article examined the design aspects of a high-performance concrete mixture constructed from fly ash and silica fumes.	All mixes showed lower workability values than the control mixture.
Raad and Assaad. [52]	2021	This study investigated the impact of adding polymer plastic waste on the structural properties of concrete.	These types of fibre reduced the ultimate shear load and flexural strength of the reinforced concrete.

Li and Liu. [44]	2020	This paper investigated the impact of different percentages of steel fibre on the water permeability of concrete by using a controlled compressive load.	The increase in the permeability coefficient of the samples was not notable.
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According to the above discussion on previous research, the evolution of concrete reinforcement was mainly influenced by mixing procedures and methods. To achieve optimal values of performance parameters, very good mixing is required. However, mixing procedures have their challenges, and it is important to understand these before holding any discussion of the optimization of reinforcement. The next section provides a brief discussion to cover these key challenges.

2.4 Challenges in Mixing Fibres

2.4.1 Selecting the Ratio of Mixing Materials

The making of a FRC mixture involves the determination of a suitable ratio of fibres to achieve the required characteristics. Mixing fibres can enhance and/or modify properties, such as durability, workability, crack resistance, elastic modulus, density and thermal conductivity [53,54]. However, the exact quantitative increase in these properties with the ratios of the fibres is not mapped comprehensively in the available literature. In the published literature, researchers have discussed the qualitative influence and impact on overall concrete performance with an increase and decrease in fibre ratio. Researchers have, for example, demonstrated that the strength of concrete can increase with the use of small size fibres [55,56].

2.4.2 Limiting Water Content in the Resultant Mix

The water ratio has a significant impact on the properties of concrete, especially on compressive strength and durability. However, due to fibre reinforcement, the

mixing of water content can be challenging, as the fibres are often randomly distributed. Fibre addition reduces workability, as it limits the smooth mixing of water content in the concrete mixture. Compliance with flow and cohesion criteria are important in designing a concrete mixture. For example, in the design of self-compatible concrete mixes with reinforced fibres, it emerged, as anticipated, that they must also meet the criterion of a good flow of concrete [57,58].

2.4.3 Selection of the Correct Accelerator

Concrete production requires control of the water content, the selection of appropriate accelerators and the regulation of air retention. Accelerators have a significant influence on short- and long-term strengths of concrete, as they enhance early strength, decrease the bounce effect and overcome earth relaxation. Yun et al. observed that steel fibres incorporated with accelerators increased the strength of concrete in the long and short term. However, alkali-free accelerator was safer than cement mineral and aluminate for workers and the environment [59]. In another study, the use of accelerators had a great impact on the mechanical properties of FRC [60]. Other researchers have noted that polyolefin fibres and accelerators can significantly improve the properties of reinforced concrete, especially for marine structure applications [61]. The selection of the correct type of accelerator is very important and highly challenging. It has been observed that accelerators tend to react chemically with the metallic fibres used during reinforcement. The impact of this reaction on the resultant concrete properties is still unexplored and hence makes selection difficult. Accelerators increase curing set-up time and, in the case of a chemical reaction with fibres, can be complex to quantify.

2.4.4 Controlling Air Bubbles

The stability of the air bubbles in fresh concrete is affected by numerous factors, such as mixing, air-entraining agents, temperature, chemical additives and atmospheric pressure [62,63]. The uneven distribution of air bubbles and fibres can adversely affect the homogeneity of the concrete, which can change mechanical characteristic and workability [64–69]. In the past, air bubbles and steel fibres were assumed to be uniformly and randomly distributed, respectively,

in a concrete matrix. Moreover, in many case, UHPC was observed to have a random distribution for both [70,71]. Wang et al. demonstrated that adding a lower dosage of superplasticizer to UHPC can distribute air bubbles and steel fibre uniformly [72].

2.4.5 Controlling Undesired Chemical Reactions

Researchers have confirmed that a suitable quantity of fibres can delay the rate of carbonation in concrete with fibre compared with normal concrete because carbonation is associated with matrix porosity, permeability and pore structure. The optimal fibre ratio plays a significant function in carbonation. The true ratio and its relation to the rate of carbonation is still unexplored and challenging to quantify [73,74]. It has been found that alkali-aggregate reaction has a negative impact on the strength of FRC constructions [75]. In other work, the cracking onset produced by the corrosion of the steel used to reinforce UHPC is delayed by the reinforcement of the fibre [76]. Paewchompoo et al. explained that was associated with the resistance of FRC due to the stopping of micro-cracks by the fibres (mixing PP and steel) throughout the treatment [77,78].

The challenges relating to adding fibres to a concrete mixture could, if fully addressed, provide desirable properties. However, a great deal of research is still required to explore these challenges and their relative impact on resultant concrete properties. One of the key elements that can influence resultant concrete properties is the fibre material. A large number of academic articles have provided observations regarding how a fibre material can have an impact on fibre mixing and the resultant concrete properties. The following section provides a discussion based on these articles.

2.5 Influence of Fibre Material in the Reinforcement of Concrete and its Properties

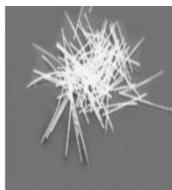
The material of the fibres used to reinforce concrete is mainly responsible for changing the properties of the concrete. In the past, researchers used fibres from different materials and provided their observations. For example, Noaman et al. added crumb rubber for reinforcement and observed a negative impact on the

mechanical properties of the resultant concrete. At the same time, however, the properties of the rubber increased the crack-resistant properties. They later added steel fibres to the same mix and found a good impact on the overall energy absorption of the resultant concrete [79,80]. Alsaif et al. reported a decrease in compressive strength and elastic modulus after reinforcing concrete with steel fibres and testing it after 28 days. They also found an improvement in these two parameters after 150 days of testing [81]. In contrast, Olivito and Zuccarello observed no increase in the aforementioned parameters after adding steel fibres [11]. The description of these articles demonstrates the significance and limitations of previous investigations without a special emphasis on reinforcement optimisation and structural performance against real-life load.

In their study, Islam et al. used polyethylene terephthalate (PET) in place of aggregate and found lesser bonding in the resultant concrete [82]. The researchers demonstrated the mechanical properties of UHP-FRC and found that fibres increased stress resistance. Similarly, other researchers replaced coarse, fine aggregates with fibres to enhance the mechanical properties of concrete [83–85]. Research has also indicated that FRC can improve post-cracking behaviour in comparison with standard concrete [86,87]. Alsaif et al. found that the density of concrete decreased after adding rubber due to the lower specific gravity of rubber in comparison with aggregate i.e., 0.8 for rubber and 2.65 for the aggregate [88]. Other researchers observed that steel fibre made from waste tyres enhanced the compressive strength and increased the crack resistance of concrete [89]. A number of investigations have examined the tensile strength characteristics of waste FRC. They found that waste fibres enhanced tensile strength [90–92].

Fibres obtained from a variety of forms of waste are appropriate for concrete reinforcement due to their various properties, as shown in Table-2. As shown in Table 2-2, we can divide such fibres into three categories: steel, plastic, waste material and Hybrid fibre. A detail discussion of these categories is provided in the next section.

Table 2-2 Properties of different types of fibre [93]

Fibre type	Shape	Length (mm)	Diameter (mm)	Density (g/cm ³)	Tensile strength (MPa)	Elasticity modulus (GPa)
Steel		13	0.2	7.85	1000	210
Polypropylene		12	0.02	0.91	451	4.5
Glass		12	0.012	2.7	1850	65
Basalt		12	0.01	2.67	2100	79
Polyolefin		12	1.07	0.92	350	6

2.5.1 Steel Fibre Reinforced Concrete

Steel fibres (SF) have been used to reinforce concrete since the 1950s. Earlier studies showed that the flexural strength of concrete could be improved by using SF along with recycled aggregate concrete (RAC). The results revealed that either of these materials improved the bending, tensile and compressive strengths of concrete [94].

Wu and Ren observed that the dynamic spalling strength of ultra-high performance cementitious composites (UHPCC) was improved by adding micro-straight and hook-end SF. They found that micro-straight SF was more effective than hook-end SF for the dynamic compressive strength of UHPCC at the same strain rate [7]. A few pieces of research have indicated that SF can significantly improve the dynamic behaviour of UHTCC. In contrast, a few others have found that dynamic behaviour does not improve if SF is added in high volume [95,96]. The addition of glass or basalt fibres improved the bending strength to a certain extent, but slightly decreased the compressive strength[97,98]. Conventional aggregate concrete with SF showed a slight decrease in compressive strength. The strength of concrete was considerably affected by the interfacial bonding of the cement matrix and SF, and Figure 2-4 shows that a rise in the amount of rubber could cause a gradual reduction in compressive strength and elastic modulus. There were many reasons for a decrease in the strength of the concrete, some of which are provided below [99]:

- 1) Rubber has a high absorption level.
- 2) An increase in the porosity of concrete can cause a reduction in stiffness.
- 3) The concrete may be lower in strength due to the inclusion of rubber.

The above indicates that an increase in SF can increase the maximum load capacity. As shown in Figure 2-4, the maximum loading capacity was considerably affected by the recycled aggregate. It was shown the relationship between load and displacement of the concrete sample by adding different amounts of steel fibres and replaced the normal aggregate with recycled aggregate without transverse reinforcement. [100–102]. A more quantitative investigation observed an increase of 20% in maximum load capacity with an addition of 30 kg/m³ of SF. On the other hand, there was no significant effect on compressive strength behaviour. SF was found to be more effective with recycled aggregate in comparison with natural aggregate and hence could replace the design of mixed design [103]. Li et al. pointed out that steel FRC (SFRC) obtained an acceptable plastic strain, but this was low in comparison with conventional concrete [104]. Gao et al. indicated that an increase in the toughness index and

modulus of SF reinforced-recycled coarse aggregate concrete (SFRCAC) with an increase in steel fibres [105]. The SFRCAC samples showed ductile failures and preserved their safety after shear failure [106].

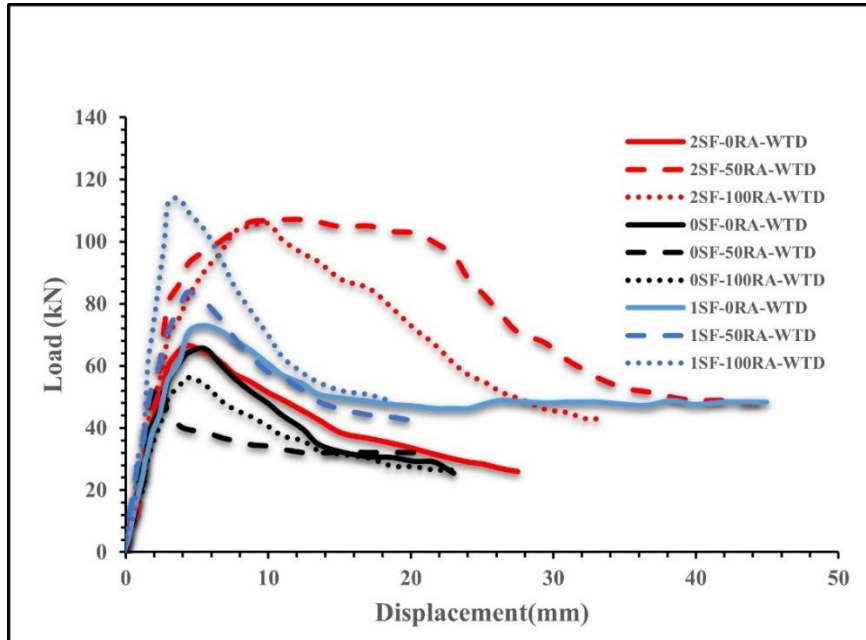


Figure 2-4 Load and displacement of samples with various recycled aggregates concrete, steel fibres with no transverse reinforcement [101].

A shear test on two types of steel fibres showed ductility in comparison with ordinary concrete [107]. However, the shear strength was high, which could be due to the small percentage and random distribution of the SF. Benefits are offered by SFRC including lower maintenance cost, higher loading capacity, reduced loading limit through cracked concrete, and greater strength. In addition, fibre simplifies joint location, reducing the work involved on site in moving steel reinforcements. It is expected that future research could lead to methods for enhancing the brittleness characteristics of concrete, bringing benefits due to the widespread application possibilities.

2.5.2 Plastic Fibre Reinforced Concrete

Plastic fibre is widely used in a number of building applications, due to its excellent crack resistance [108–110]. Research has shown that the elasticity and compressive and bending resistance of concrete are increased by raising the proportion of polyester polymer [111]. Bulut and Şahin also pointed out that

concrete that contains electronic plastic waste was more ductile than traditional concrete, although its mechanical properties were reduced with an increase in the percentage of such plastics [112]. Other researchers have indicated that density decreases with an increase in content when replacing PET with aggregate [82]. Zhang et al. demonstrated that polymer fibre bars enhanced the compressive strength and bonding behaviour of seawater sea-sand concrete [113]. In other work, Zhang et al. confirmed that basalt fibre reinforced polymer rebars increased shear capacity and flexural restraints [114,115]. Flexural and compressive strength were also found to be enhanced by adding waste plastic fibres (WPF), as shown in Figure 2-5. It has also been observed that WPF reduced workability, but that V-funnel flow time and L-box height increased. Wet density decreased for the following two reasons, as shown in Figure 2-6 [116]: The gravity of plastic is low compared with the gravities of cement and aggregate.

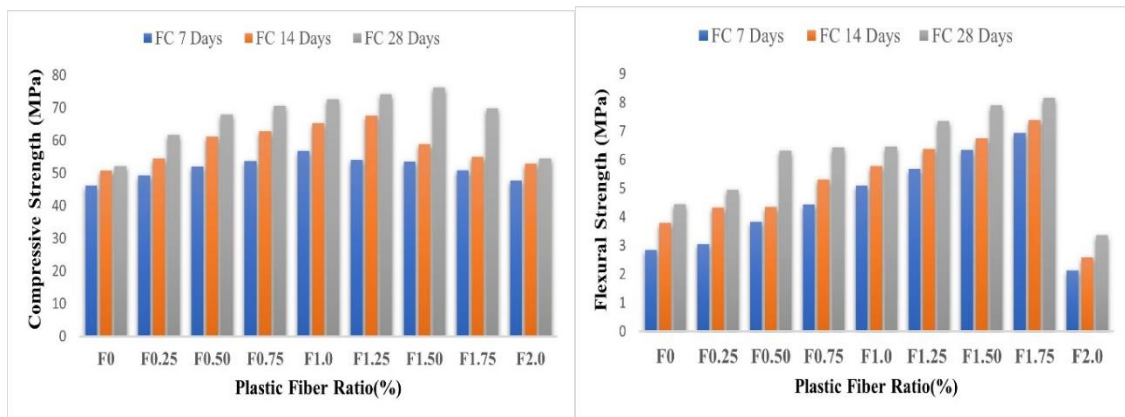


Figure 2-5 Effect of adding plastic fibre on the flexural and compressive strength of concrete [116].

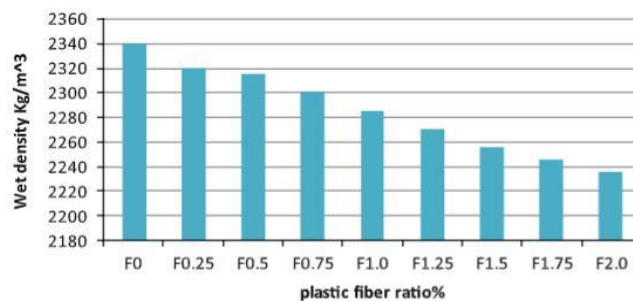


Figure 2-6 Plastic added to SCC requires more water to develop density [116].

Yang et al. found that the mechanical properties of concrete, including the split tensile, compressive, and flexural strengths of self-compacting lightweight

concrete, were improved by adding plastic fibres. However, elastic modulus, density and workability decreased [117]. Concrete with PET was also found to be more ductile in comparison with traditional concrete, with improved crack resistance [118]. During a freeze-thaw test, another study observed that the properties of concrete were improved by adding recycled PET fibre [119].

As demonstrated above, the addition of plastic fibre increases the performance of concrete, as different fibres have a high estimation for elastic modulus and improve various properties of concrete, such as: flexural strength, impact resistance, compressive properties, fatigue resistance, tensile strength, malleability, shear load of a structure, and abrasion and resistance against wear. As a result of such performance improvement, FRC has been used in a range of applications, such as water-driven structures, bridge decks, airfield pavements, uncompromising ground surfaces (industrial floors) and tunnel linings.

2.5.3 Waste Material as Fibre

In the literature, researchers have reported using waste materials as fibre to enhance the different properties of concrete, such as compressive and flexural behaviours [120,121]. Considerable improvement in flexural response was, for example, observed for concrete samples reinforced by adding waste tyres to the concrete mix [89]. The recycling of scrap tyres mainly involves separating the inner steel support from the rubber covering, and this waste material plays an important role in increasing the cracking resistance of RAC. For example, it was observed that the addition of waste fibre affected the initial cracking time, as shown in Figure 2-7 [122]. Carbon fibre waste added to concrete has a significant impact on mechanical properties, and, as a result, reduces maintenance requirements and thus improves the sustainability and durability of structures [123]. Kumar et al. observed that the combined impact of recycled steel fibres (RSF) and glass powder could also enhance the mechanical properties of concrete [124]. In similar research, it was found that the combination of fly ash and waste SF enhanced the density and mechanical performance of concrete, although the steel fibre reduced its workability [125]. Other researchers observed

that the workability requirement could be satisfied by the smooth surface of waste plastic bag fibres [126].

In other studies, concrete density was reduced by increasing the quantity of PET bottle waste, because the density of a natural aggregate is higher than that of plastic. The mechanical properties of concrete containing PET bottle waste were lower than for standard concrete because it decreased the amount of natural aggregate, which is useful for strength [127,128]. Ghernouti et al. also demonstrated that PET increased the ductility of concrete and decreased cracking, and other researchers found that concrete could be made more structurally durable by using PET in strips to reduce the use of steel [127,129–131]. Tran and Ali demonstrated that fibres have another advantage in terms of the performance of FRC, such as the decreased cost of making the concrete and environmental benefits [132,133].

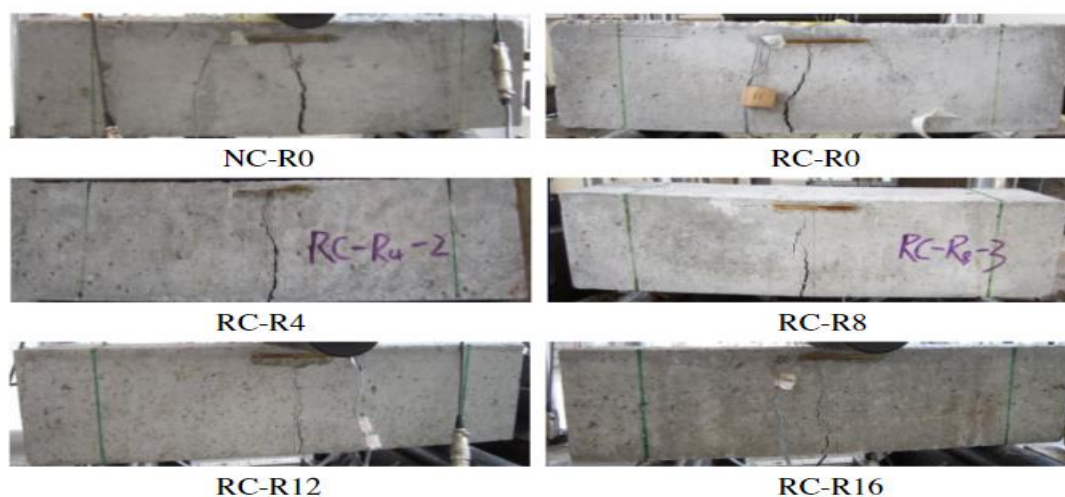


Figure 2-7 Flexural failure modes of rubber crumb and SF-reinforced RAC [122].

In summary, as demonstrated in the studies cited above, there are improvements that can be obtained from the use of waste materials as fibres, such as the lower cost of maintenance, development in load capacity and the mechanical properties of concrete, reduced cracking, and improved tensile strength.

2.5.4 Hybrid Fibre

Hybrid fibre is widely used in several construction applications, due to its excellent crack resistance and increase durability of concrete. Research has found that an

improvement in the mechanical properties and resistance of concrete by adding the steel-polypropylene hybridization. It showed that the hybrid fibre with more steel content significantly increased the impact resistance with the amount of polypropylene at 0.2% as shown in Figure 2-8. However, large sample will be useful to check the impact of strength for more accurate conclusion [134]. In addition to the impact resistance, durability was investigated by the researchers and their test results were used to improve the compressive, bending and fracture strengths of structural materials. The research observed that the effect of abrasion improved by 10 % when added the hybrid fibre to concrete at 6kg/m³[135,136]. Mehran and Mingli studied that the hybrid fibre has positive impact on fracture energy which has been considerably improved up to 258%. The researchers found that the best value of fibre hybridization was at 1% CW, 0.45% BF with 12mm length, and 0.35 % SF. This showed an improvement in concrete due to hybrid fibre in comparison with normal concrete[137–139]. Other findings showed a decrease in workability, density, and compressive strength. They also observed an increase in spilt tensile and flexural strengths [140,141].

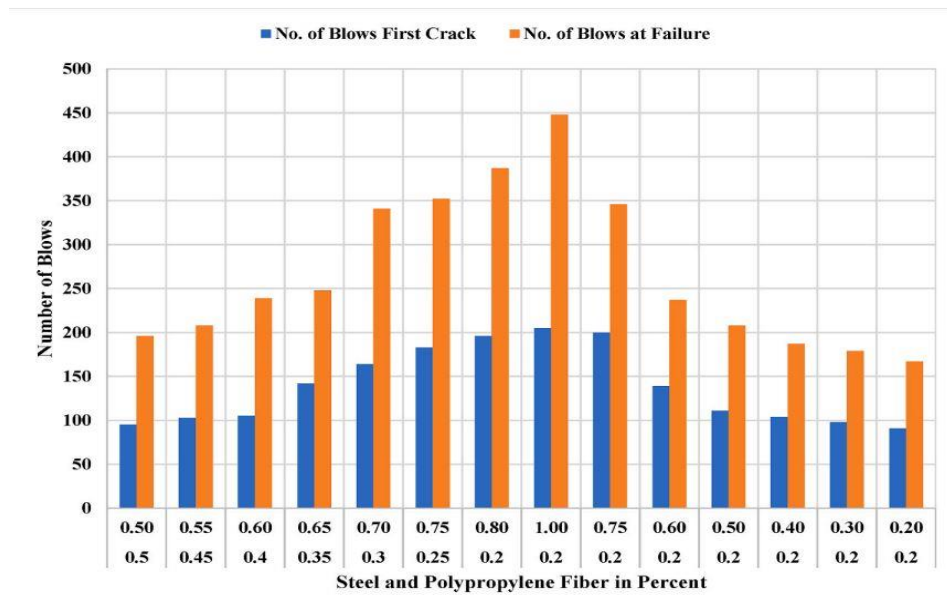


Figure 2-8 Hybrid effect on impact resistance [134].

Previous studies reported that the ductility of concrete was increased when added PVA with steel fibre. In contrast, the ductility reduced in the mix with Nylon-mono and steel fibre [142]. Zhishu and Wang observed that an improvement in

compression deformation of HFRC. This improved brittleness and the dynamic strength. The hybrid fibre also reported to enable concrete resistance against crack initiation with improve fracture toughness[143,144]. Emad et al. found that rubber reduces the compressive and tensile strengths of concrete. However, by adding steel fibre with crumb rubber considerable improvements in fractal properties were achieved. The most significant improvement of reinforced concrete hybrid fibre observed for content with 1% PP and 0.9 steel fibre [145,146].

As per the above discussed past investigations, the addition of hybrid fibre enhances the performance of concrete. Properties like impact resistance, flexural strength, fatigue resistance, compressive properties, tensile strength, malleability and durability of structures were reported to be enhanced with inclusion of such fibres.

2.6 Optimization of Reinforced Concrete

2.6.1 Optimization of Concrete Using Different Shapes and Types of Fibre

The shape of the fibres added to concrete affects the properties of the material. Stereological standards have been set for the appropriate characteristics of fibres in terms of their size and boundary zones. Symmetrical proficiency factors are also taken into account for 1D, 2D and 3D fibre divisions, which are combined to form an effective approach in the direct planar "Stroeven" framework method [147]. Different types of post-consumer plastics, such as PP, polycarbonate and glass reinforced plastic, have been used to reinforce concrete [148–150]. Research has also been conducted into high concrete performance that was consolidated with plastic bottle fibre portions of different volumes, shapes and lengths, and it was observed that tensile strength decreased with the additional content of fibres [151] and that both short and long steel fibres reduced the propagation of micro-cracks, as shown in Figure 2-9 [152]. The majority of researcher did not consider the shape, types and percentage together in their study of fibre to find the optimal value of fibre reinforced concrete.

Over 90% of the SF available is engineering steel fibre (ESF), with twisted finishes, treated surfaces, and bent, hooked end, and pleated fibres, as shown in Figure 2-10. The ESFs examined have been revealed to be significantly better than normal fibres. For example, the aspect proportion and other geometrical properties are not related to changes in the mechanical properties of ESFs [153].

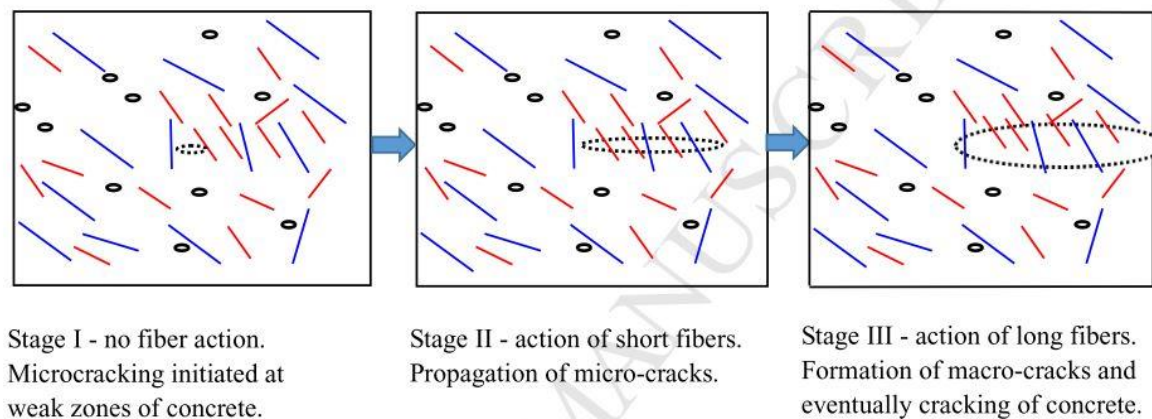


Figure 2-9 Crack restraint by adding hybrid SF reinforcements to UHPC [152].

According to Pereira et al., the load capacity of a natural concrete produced with PET fibres is better than that of traditional concrete. This is one of the areas in which the inclusion of fibres from PET containers to concrete has enhanced the mechanical properties of ordinary concrete in terms of tension, bending and compressive strength. The synergistic impact of variables relating to fibre volume and fibre length appears to have an effect on the tensile strength of concrete [154]. In other work, a bond resistance of 16 mm was higher than that of 20 mm WPF in all the examples examined. Figure 2-11 shows one of the plastic fibre types used [116].

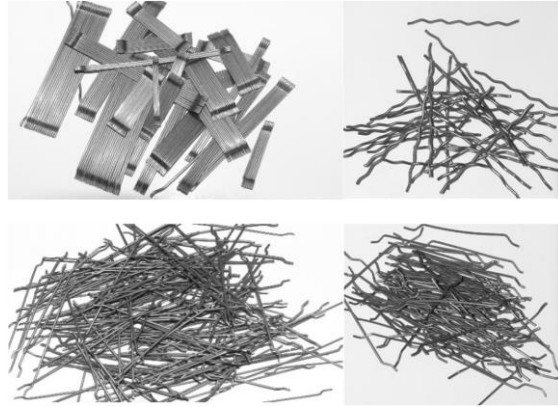


Figure 2-10 Examples of geometric shapes for commonly used ESF [79].

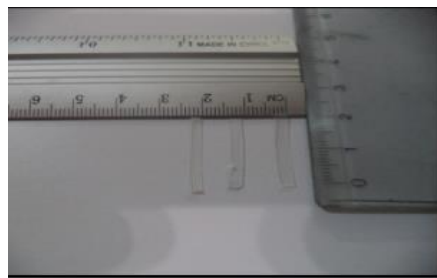


Figure 2-11 Shredded waste plastic [116] .

2.6.2 Optimization of Fibre Volume

Adding fibre at a particular volume fraction increases ductility and improves the properties of concrete. Researchers have tested various volume fractions to ascertain the optimal percentage of fibre for reinforced concrete [155]. Gao et al., for example, investigated the failure mode and mechanical properties of concrete with various amounts of steel fibre (0%, 0.5%, 1%, 1.5% and 2%) [106]. In other work, Youssf et al. studied the influence of FRP confined and unconfined crumb rubber concrete with a high amount of rubber on the mechanical proprieties of concrete, in which rubber replaced sand in the following percentages: 0%, 10%, 20%, 30% and 40% as shown in Figure 2-12 [156]. Another study showed that the addition of SF improved static and dynamic mechanical properties when using the optimal amounts of short and long steel fibres, which were 0.5% and 1.5%, respectively [157]. In order to enhance fracture behaviour, the optimal volume of SF was found to be 1%, as shown in Figure-11. However, high-temperature exposure decreased the loading capacity of the sample [158]. In practical terms, a small proportion of short fibres used during blending (generally around 0.5-1.0% by volume) brings about improvements in toughness in the post-cracking of

cementitious materials, as those fibres have a connecting impact over an opening crack and a positive effect on the distribution at that point [159].

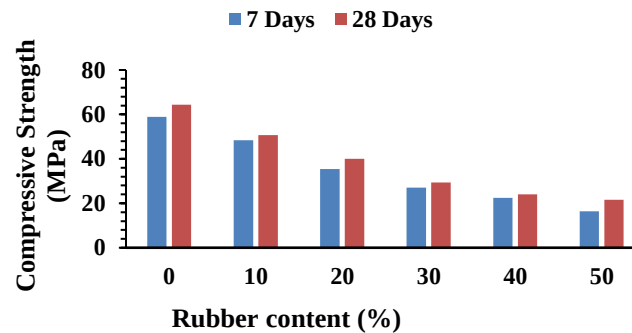


Figure 2-12 Effect of rubber content on compressive strength [156].

The optimum ratio of fibres per quantity of concrete has been found to be between 0.5% and 1%. Depending on the type of fibre, previous work has investigated the effect of the percentage of fibres based on the workability and flexural, split tensile and compressive strengths of the concrete produced. However, still a comprehensive effort is required to investigate the effect of content fibres on more realistic loads such as thermo-mechanical and dynamic load.

2.7 Testing the Optimization of FRC Properties

2.7.1 Workability

Studies have reported the various factors that must be considered in the optimal casting of concretes. A collapsed slump and a zero slump are, for example, both external to the range of the types of workability that can be included in a workability test, as shown in Figure 2-13 [160]. The factors that must be considered include construction type, the standards to use and the methods that should be followed. In addition to the basic structures, there are complexities in the casting and the finer points of construction that have an impact on the extent of the reinforcement of the structure. As the structural use of concrete grows to encompass auxiliary execution, a greater need has arisen for high-flow cement for form-filling. These elements may be challenging to reconcile, as there are constraints to poker vibration and the force needed to fill an area optimally.

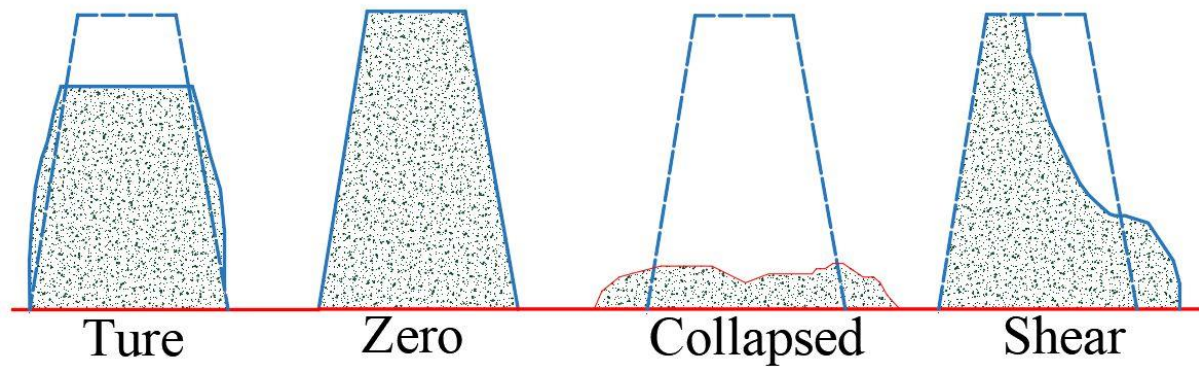


Figure 2-13 Types of workability [160].

As this type of general concrete has a high level of fluidity, over-vibrating it can cause it to separate, distort and fail in the spreading space between reinforcements. Thus, workers are required to have a strong level of skill and a strict focus on quality standards in order to ensure that the concrete cast is homogenous and adequate pressure is attained. This requires effort and time, and testing processes must be available that can rapidly measure workability, with further work needed to develop this area. Current testing procedures provide a foundation for the discussion of theories and models that have not been fully developed and which could inform further testing strategies [160]. Recent research attention has turned to workability in assessing fibre concrete production possibilities, and various researchers have applied slump tests, as these appear to be reliable and simple in their application. In [28], the authors report decreases in workability with an increased fibre content of the concrete sample, and another study found reduced fresh concrete workability when either of two kinds of SF were added [161]. It has also recently been reported that both rubber and SF additions caused workability to decrease [81]; this was also found in [88], in which the authors suggest that this could be due to reductions in free water due to the added rubber. Leone et al. found that a good workability level was found with the addition of either industrial or recycled short SF. Workability was reported not to show an impact with a small amount of added SF [107]. Adding WPF to concrete also reduced the workability of fresh concrete, as shown in Figure 2-14 [116].

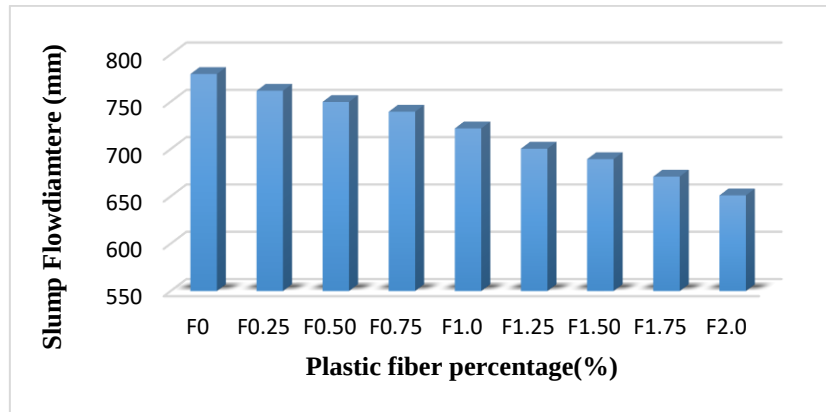


Figure 2-14 Impact of plastic fibre on the workability of fresh concrete [116].

Concrete workability was also found to reduce as the level of low-grade SF additions increased [103]. Decreases in workability with increased SF use could be due to low levels of superplasticizer, in which the added fibres also reduced workability. This might be mitigated by adding superplasticizer [162,163]. In comparison with a control sample, concrete containing PET aggregate concrete displayed greater workability [82]. Other researchers found that slump values were enhanced at plastic levels below 20%, with slump loss reductions of as much as 30% [117]. Workability was also found to decrease when PET was added, which was attributed to the sharpness of PET increasing the water requirements of the concrete [164]. They found that all types of fibre reduced the workability, but they can avoid this issue by adding materials improve the workability such as superplasticizer for Concrete vibrating equipment.

Based on recent studies, the shape and ratio of the fibres added have a great impact on concrete flow and the degree of skill that workers require to produce high-quality concrete structures. Investigating greater levels of cement or fine aggregate or fibre additions could be beneficial in this area, as increasing fibre additions may change sample responses and lead to development in which the shape of fibres is modified to target greater workability [93,147].

2.7.2 Mechanical Properties

2.7.2.1 Quasi-static loads

2.7.2.2 Compressive strength

An essential attribute of concrete when managing quality is compressive strength and, therefore, work to develop and improve different concrete types and classes should involve investigation of this characteristic [166]. A calculation of the compressive strength of a sample is determined by dividing the highest load applied to the sample during the test by the cross-sectional area, determined by the mean dimensions of the section, and recorded to the closest kg per cm². Recently, various researchers have contributed to a comprehensive review of the mechanical properties of concrete, including its compressive strength. As noted, compressive strength decreases as the proportion of fibres increases in the concrete [28]. Moreover, compressive strength was found to be reduced with an increase in WPF values because the fibre lowered the workability of the mix, which grew porous [167]. However, other researchers reported that the addition of silica fume to steel fibre RAC (SRAC) after exposure to high temperature achieved significantly improved compressive strength, toughness and elastic modulus [10,168]. A slight effect on compressive strength was reported after adding two types of SF [107]. Similar effects on compressive strength were also found in both SFRCAC and standard concrete [169]. Other results have suggested that the compressive strength of concrete using recycled tyre steel fibres and recycled tyre steel cords was greater than for SFRC [170]. Other researchers found that the compressive strength of RAC was about 72.26% of natural aggregate concrete but, after adding silica fume, the compressive strength of concrete with recycled PET increased slightly (by about 3.6-9%), as shown in Figure 2-15 [171]. The effect of steel and plastic have been investigated by past researcher. the steel fibre increased but not very significant .in case of plastic fibre, no impact has been observed.in addition, they did not consider the long-term impact of fibre on compressive.

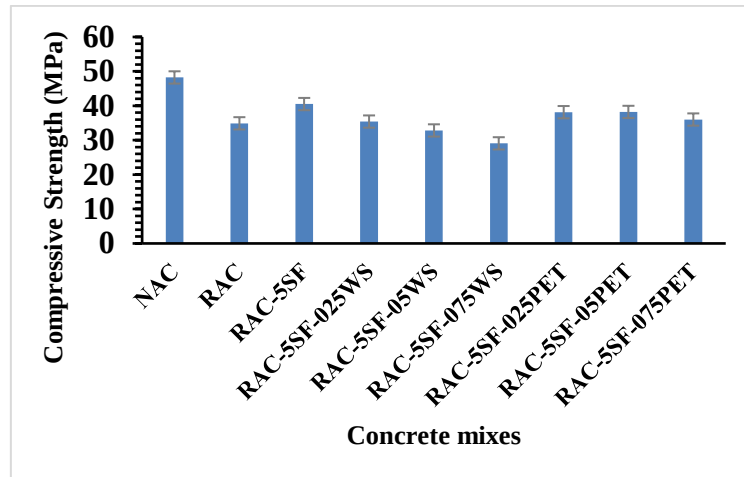


Figure 2-15 Compressive strength of concrete mixtures [171].

Furthermore, with the addition of SF, compressive strength increased for two aggregates (normal and recycled), by about 12% after 28 days [103]. However, in another study, the compressive strength of the concrete was too low. Two potential reasons were identified: when RAC replacement increases, it reduces the water-cement ratio and has effects either due to the shape or volume of the steel fibres [106]. An increasing amount of rubber was also found to reduce compressive strength in two mixes [172]. Other results indicate that compressive strength increased slightly with a greater amount of both types of SF. However, the compressive strength, elastic modulus and toughness of SFRAC decreased when exposed to a temperature of around 400 °C, although the addition of silica fume was found to enhance the compressive strength properties of SRAC [173]. Other findings show a decrease in compressive strength with the addition of e-plastic due to the replacement of the aggregate with plastic [112]. Compressive strength was affected only with greater volume fractions of fibre added to the concrete. The standard models created could be adopted to predict the compressive strength value [154].

Su et al. indicated that the addition of SF to UHPC increases compressive strength, as shown in Table 2-3 [174]. Other researchers found no significant effects on compressive strength with the use of SF [175–177]. The addition of waste PET was also found to reduce compressive strength because the concrete had a low water-to-cement ratio and high workability and the amount of PET

added to the concrete as aggregate, because the surface of a natural aggregate had a stronger bond than PET [82].

Table-2-3 Experimental results of different formula UHPC under compressive load [174].

Fibre type	MF15	MF06	TF03	TF05
Strength (MPa)	145.12	114.51	132.29	113.05

In other work, the compressive strength of lightweight SCC was found to decrease by approximately 12% compared with concrete without SF [178]. However, Caggiano et al. reported that compressive strength appeared not to be affected when adding steel and PP fibres to concrete, as shown in Figure 2-16 [179]. Noaman et al. found that compressive strength increased with the addition of SF up to 0.50% [180]. A high value for SF was also associated with a decrease in the mechanical properties in comparison with standard concrete [181]. Other researchers ascertained that the elastic modulus and compressive strength of polymer concrete (PC) produced with benzoyl peroxide (BPO) were less than for PC with methyl ethyl ketone peroxide (MEKP) [182].

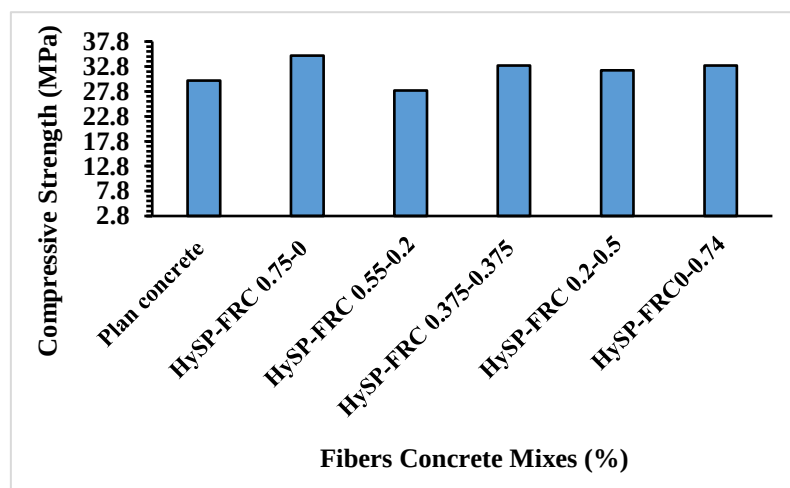


Figure 2-16 Compressive strength of HySP-FRCs [179].

2.7.2.3 Tensile strength

The tensile strength of concrete is increasingly becoming a consideration, due its impact on structure durability, load capacity and fracture properties [183]. The previous study reported that ductility was improved by adding fibres and that

tensile strength increased in two types of SF added to concrete, as shown in Figure 2-17 [184]. Similarly, tensile strength and ductility were shown to increase by raising the WPF content, due to greater ultimate applied load and decreased internal stresses, [167]. Moreover, tensile strength was found to increase with SF and RAC without fibres by 9-16.6%. The elastic modulus of RAC was shown to reduce with an increased value of recycled woven plastic sack waste as shown in Figure 2-18 [185]. In their study, Leone et al. indicated that there were no significant effects on tensile strength with the use of SF, finding only slight effects on tensile strength through SF added to both types [107].

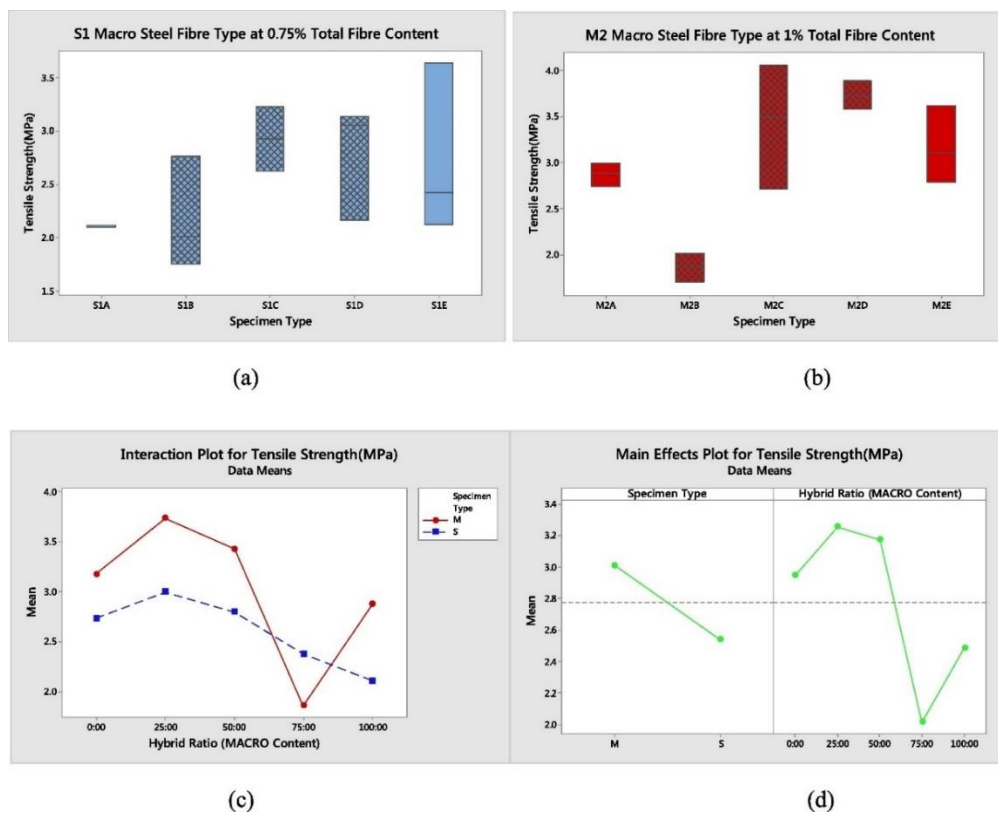


Figure 2-17 Increase in tensile strength with two types of SF [184].

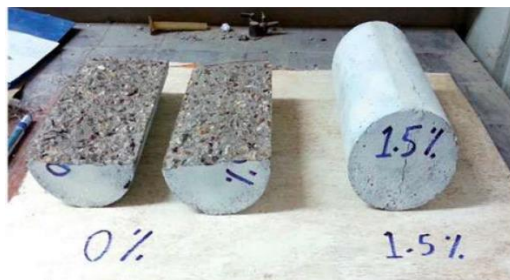


Figure 2-18 Comparison between specimens with the highest PET fibre percentage directly after the test [185].

According to Pereira et al., there was a significant influence on the tensile strength of concrete with fibre compared with the reference concrete [186]. The researchers suggested that a decrease in tensile strength with the addition of e-plastic was due to the replacement of the aggregate with e-plastic. However, an increase in tensile properties with a higher percentage of e-plastic waste was attributed to the increased ratio of resin resulting in better moistening and encasement of the gaps in the materials [112]. Abbass et al. demonstrated that the tensile strength increases with the addition of steel SF content. However, one configuration was found to have a lower water-to-cement ratio and showed a reduction in tensile strength, as shown in Figure 2-19 [10,95,187]. However, an overall effort is still needed to study the effect of content, percentage, and type.

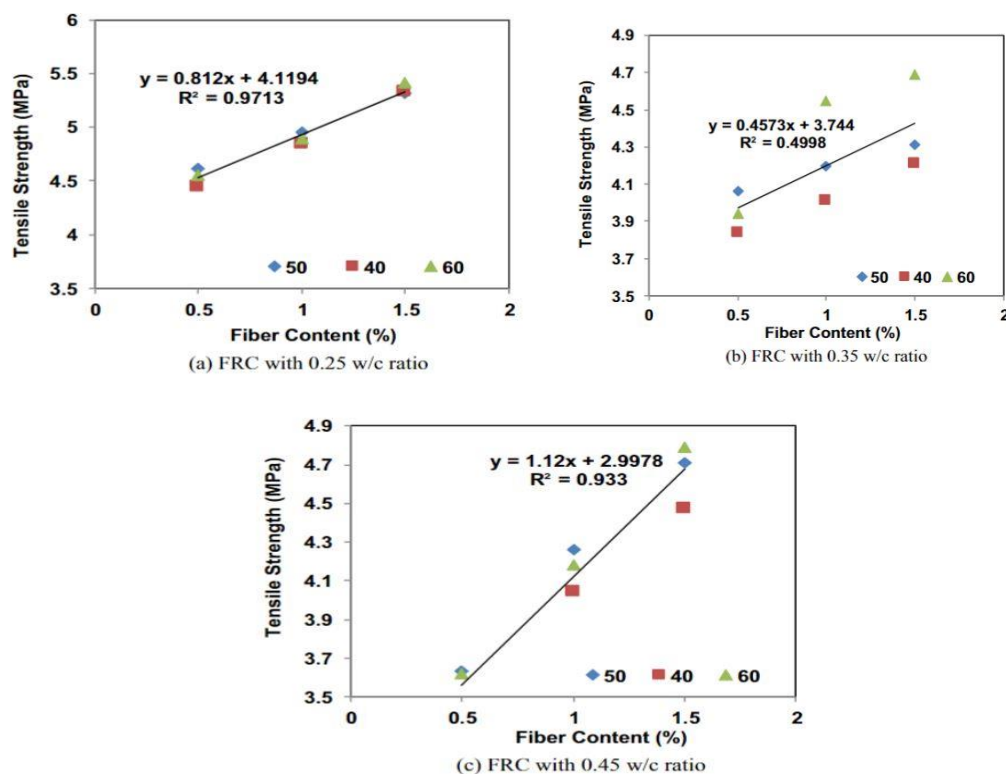


Figure 2-19 Lower water-to-cement ratio showing a decrease in tensile strength [10].

2.7.2.4 Flexural strength

Flexural strength is a measure that is often applied in relation to structural concrete. It is tested the bending based a method of third point loading as in ASTM-C78 (2010) by using the prism specimen test, or on centrally positioned loads, as set out in ASTM C293 (2015), until failure. The second method is the one most frequently applied and is mainly accepted as offering greater value in comparison with other approaches [188,189]. The impacts from flexural strength are considered an important measure for the design of basic structural components, such as shafts and cantilevers: Previous studies have reported that adding steel and plastic fibres to standard concrete improves crack resistance and reduces cracking Flexural strength increased as two types of steel fibres were added to concrete as shown in Figure 2-20 [184]. In one study, flexural strength enhancement of reinforced RAC was found to be approximately 43% by adding waste fibre [190]. Yap et al. found that SF additions improved mechanical properties, including resistance to cracking and toughness [191], and Monteiro et al. showed that hooked-end SF was more effective in increasing resistance to crack growth due to its geometrical properties and material [192]. A study reported by Iqbal et al. found an increase in flexural strength and tensile strength of around 110% and 37%, respectively [161].

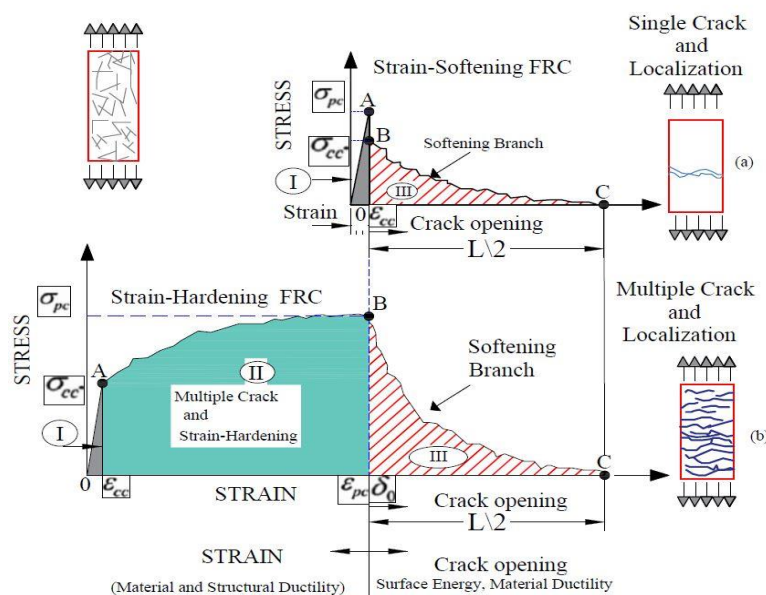


Figure 2-20 Increased flexural strength in two types of steel fibre [184].

Another study findings supported the approach of increasing flexural strength by raising PP fibre content, as this showed flexural performance improvement in both equivalent flexural strength and toughness with an increase in the proportion of SF used [193,194]. Moreover, there was a significant positive correlation between the type of FRP added to concrete. A positive correlation was also found between steel and PP after adding different volumes to concrete, which enhanced the post-cracking behaviour of the cement material [195]. According to above investigation the fibre was increased the flexural, but an overall effort is still needed to study the effect of content, percentage and type.

However, an increased strain rate was found to cause a higher amount of cracking. The transverse reinforcement spacing was 100 mm to affect flexural strength when adding the steel fibre [101]. On the other hand, flexural capacity was developed by using 200 mm spacing, and increasing the SF improved the failure mode from shear to bending. The addition of industrial SF (ISF) and RSF improved flexural strength behaviour [107]. Flexural strength was increased by less when using a volume of below 0.5% SF, and between 0.5% and 1.0% content of SFRCAC, but the toughness and flexural strength rose slightly [169]. Papastergiou et al. demonstrated that cracks were more significant in hollow beams without fibres. However, by adding SF to the hollow beams, cracking was reduced and the load capacity increased. Furthermore, the flexural strength of recycled SFRC is reported as being considerably higher (about 103%) than for concrete with ISF. Flexural strength performance develops with increases in the value of RSF [170]. Ductility was also shown to be improved by adding fibre, which significantly enhanced flexural strength. Post-cracking was improved by using both ISF and RSF [107]. Furthermore, the number of cracks in hollow beams has been shown to be lower than for traditional concrete. This may be due to bending influences in the tensile area being reduced by entering an empty longitudinal hole [196]. For both plain reactive powder concrete and SF-

reinforced reactive powder concrete, the compressive strength increased with a rise in strain rate [197].

Li et al. reported that the concrete in their study had a considerably increased flexural strength, and that a useful shear crack mode could be achieved with SFRC compared with standard concrete [104]. Other results indicate, however, that there were no significant effects on flexural strength of the use of SF, and that this may be due to the amount and type of fibres used [198]. There was no apparent cracking in concrete samples with 20% rubber [172]. Bending was found to be highly influenced by using ISF and RSF reinforced concrete, which reduced cracking. However, ISF reinforced concrete showed slightly reduced toughness and ductility, especially for the opening of small cracks. The reason for this was probably the amount and diameter of the fibre [173].

Another study shows considerably improved both initial crack and ultimate failure, and found that SFRP and crumb rubber fibre (CRF) together improved dynamic concrete properties [180]. Experimental testing has also shown a significant influence on bending behaviours by adding fibre [89]. According to an investigation by Abbas et al., an increase in mechanical properties also occurred with a rise in the volume of SF [199]. Furthermore, a mix incorporating short SF enhanced flexural strength compared with the same mix and volume of long SF [178]. Another study found that the mode of concrete changed from brittle to ductile and there was a significant impact on post-cracking and a reduction in cracking [11]. The bond strength of PC made with MEKP was also found to be higher than for concrete with BPO. However, increasing PET to PC with MEKP from 1:1 to 2:1 decreased the bond strength of the PC [182]. Flexural and tensile strengths were improved compared with the control concrete. However, compressive strength was not affected after 28 days [126]. Other results found a decrease in flexural strength with the addition of e-plastic due to replacement of the aggregate with plastic [112]. In another study, flexural strength increased because recycled WPF improved crack resistance, developing ductility and controlling crack size [171]. Other researchers found that flexural strength increased and obtained a higher peak load when increasing the content of the

fraction, but post-cracking with a short fraction was smaller than with a larger fraction [200]. Further results show that flexural strength increased for two lengths of fibre (20 mm and 50 mm), as illustrated in Figure 2-21, compared with standard concrete [201]. The control concrete failed in brittle mode, whereas concrete with recycled WPF failed in ductile mode. Finally, cracking was reduced significantly for all lengths and volume fractions tested [202].

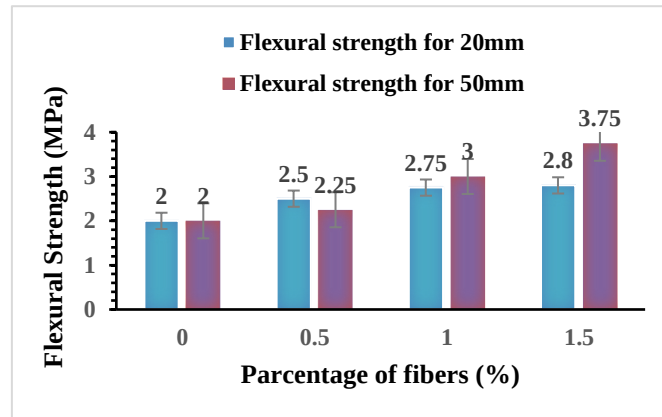


Figure 2-21 Comparison of flexural strength for mortar mixtures [201].

2.7.2.5 Fracture energy

The fracture energy of concrete is a fundamental property required for the accurate estimation of brittle failures of concrete construction [203]. The fracture zone of concrete is shown in Figure 2-22[204]. Raj et al. investigated the impact of SF and rubber additions to concrete. When added at approximately 1% SF and 15% rubber, the fracture energy improved by 90%. However, when 0.3% PP fibre was added, the fracture energy was enhanced by only 47% [205]. Fracture energy was found to increase with SF hybridization of up to 70%, but decreased when using just macro SF [184]. Other researchers found that fracture energy increased by approximately 37% when adding 25% rubber, and 0.5% hooked-end SF raised fracture energy by nearly 152% [206]. Figure 2-23 shows the association between two fracture energies for the fibre types examined (Fig2-23 a, b) [207].

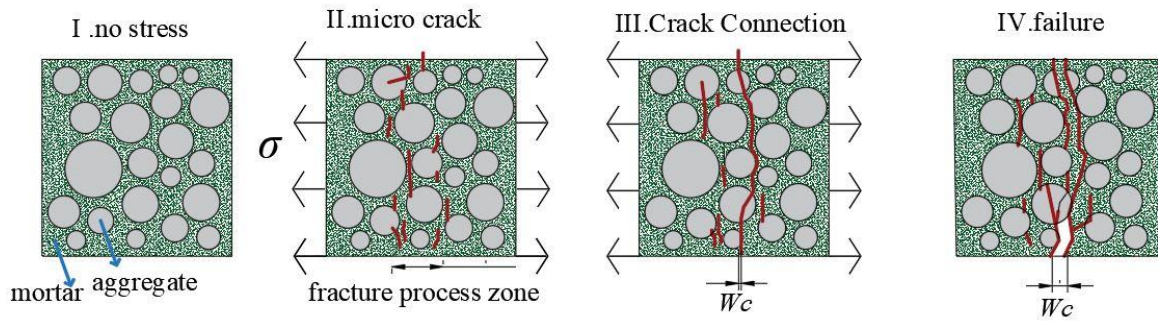


Figure 2-22 Fracture energy zone of concrete [204].

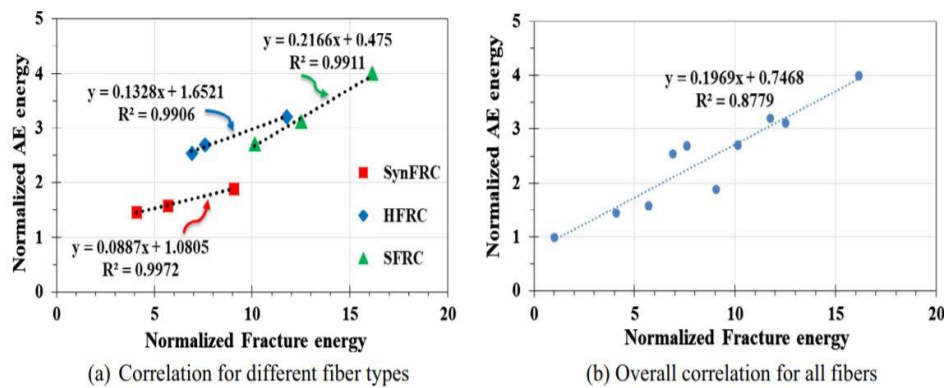


Figure 2-23 Relationship between normalized fracture energy and normalized acoustic emission energy [207].

In their study, Noaman et al. demonstrated an improvement in fracture energy through the consolidation of rubber chips as a partial substitution for aggregate [206]. The highest measure found for fracture energy (G_f) was 12%, which brought about an improved retained fracture and energy model when contrasted with standard concrete (PC) [208]. Depending on the requirements, studies suggest restricting the content of morsel elastic aggregates to up to 10% of the volume of fine and coarse rubber aggregates to improve fracture energy and reduce decreases in bending strength [209]. Utilizing rubber from destroyed tyres with steel wire belts was found to be an excellent solution compared with those without steel wire belts [210].

2.7.2.6 Fatigue life of FRC

Fatigue is challenging, as the bond joining carbon fibre reinforced polymers (CFRP) and steel is essential. Bonding failure is the predominant failure in SF systems, although this is not the case in concrete-FRP structures [211–216]. Depending on the fatigue performance of concrete and FRP support, long-term serviceability may be influenced by both non-strengthened and reinforced concrete beams [217]. Other researchers have stated that numerous structural parameters of concrete elements, for example, tensile and compressive strengths, fatigue life, and Young's modulus, among numerous others, show basic dispersal. Investigation of concrete fatigue life typically yields test results that can differ by two sets of extent, when ‘identical’ solid examples subject to ‘identical’ cyclic loads are considered. Dissipated impacts are seen in plain concrete, as well as in FRC [218]. Banjara and Ramanjaneyulu found that the fatigue life of FRC can be assessed according to the portion of the fibre content fraction, as shown in Figure 2-24 [219–222].

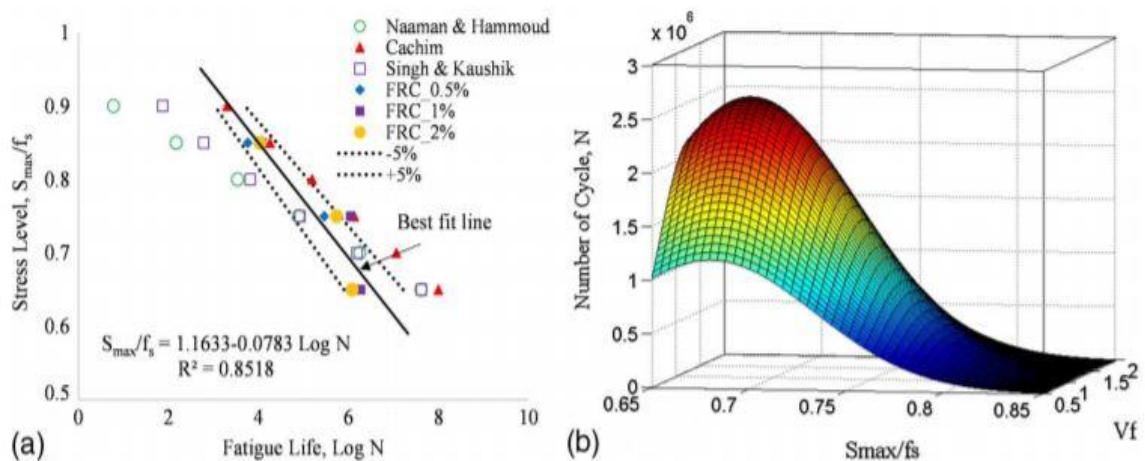


Figure 2-24 Shows S-N curves for FRC using flexural fatigue loading: (a) comparison of S-N models for FRC; and (b) impact of the FR volume on the S-N curve [222].

CFRP reinforcement in strengthening concrete beams seems appropriate as an intelligent system for setting the fatigue life of a reinforced concrete beam that

has failed tensile steel, or as a way to increase fatigue life [223]. FRP composites were found to bring about higher resistance from fatigue in comparison with other design materials [224,225]. Matsumoto investigated the impact of FRC on fatigue life using a theoretical investigation via a fracture mechanics-based model and found that FRC increases the fatigue life [226]. The addition of SF was found to be significant in improving the strength of concrete and its fatigue life, as it avoided the open crack area [227]. According to above investigation the fibre was improve the fatigue life, but an overall effort is still needed to study the effects of content, percentage and type.

2.8 Testing Fibre Reinforced Concrete Properties under Thermo-Mechanical Loads

FRC has been investigated in recent decades for increased crack control. Further significance is found when fibres are combined with a naturally brittle material: for instance, high-strength concrete (HSC), the utilization of which has expanded gradually, is not simply due to its higher load-bearing capacity [228]. Therefore, because of the increase in service life and durability, the higher load-conveying boundary of HSC is commonly accompanied by progressively more brittle behaviour, which can be mitigated by the consolidation of fibres. Various investigations on the degradation of concrete when subject to high temperatures have been conducted. Concrete structures could be subject to high temperatures, coincidental causes or the attributes of auxiliary application and, as a result, concrete changes, which may affect its mechanical properties [229]. Different researchers have considered the influence of adding polymeric fibres to concrete under thermo-mechanical loads [230–232].

Several researchers have studied the impact of thermo-mechanical loads on FRC. According to [233], there was an explicit reduction in compressive strength at high temperature compared with ambient temperature. However, 3D and 5D SF added to increases in compressive strength compared with 1D SF concrete, at about 75 kg/m³ and 45 kg/m³, respectively. Moreover, there was a small loss of density in the concrete due to its reduced water content, as similarly reported

by [234]. Therefore, there was no change in the compressive strength and elastic modulus of concrete with and without fibres. However, there was a significant increase in tensile and bending strength when adding both steel and PP fibres at between 40% and 150%. Treviño et al. demonstrated that the conductivity, due to the thermal process for standard concrete and FRC, was reduced by about 7%. Electrical resistivity was not an influencing parameter when checking the damage accrued by using microwaves in the method used. The results indicate that flexural strength decreased by around 50% and 32% at 320 s and 240 s microwave heating, respectively, as shown in Figure 2-25[235]. Moreover, researchers have indicated that adding PP to mixes reduced the spalling of concrete at high temperatures. The density of all the samples considered was decreased by approximately 2375 kg/m³, 2325 kg/m³, 2275 kg/m³ and 2225 kg/m³ by increasing the temperature to 20 °C, 200 °C, 400 °C and 600 °C, respectively. Compressive and tensile strengths sharply decreased when the temperature increased, as shown in Figure 2-26 [236].

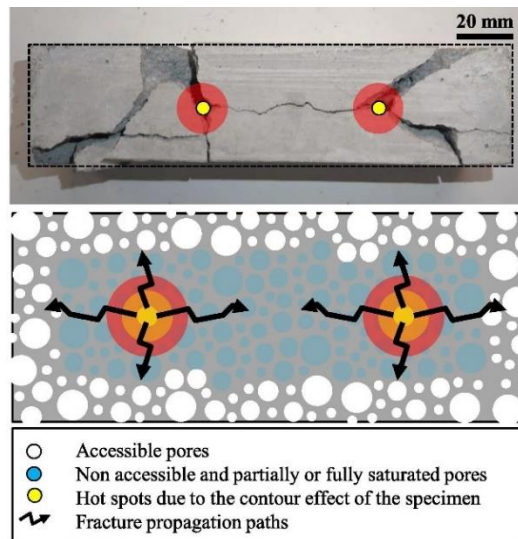


Figure 2-25 Reshaped intermittent reference mortar after a microwave circle of 300–400 s and cracks beginning and spreading on a prismatic sample [235].

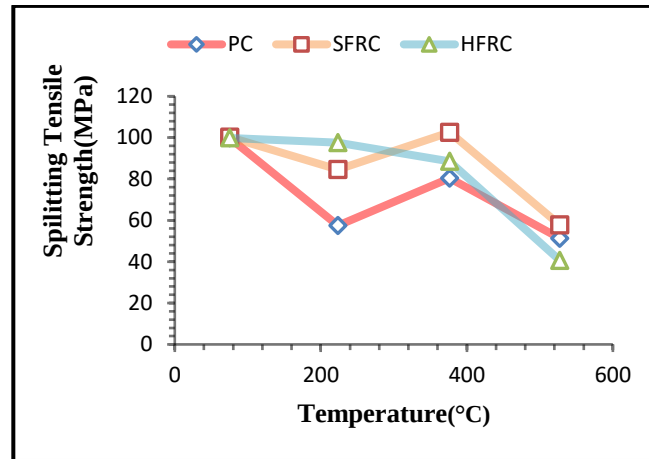


Figure 2-26 Split tensile strength of concrete at high temperature [236].

Researchers have identified the most convenient FRP composites among the possibilities investigated in order to achieve the best fatigue performance in comparison with concrete without FRP under exposure to high temperature. A spalling mechanism was employed using an electric furnace and scanning electron microscopy tests were performed to determine the microstructure of polypropylene-fibre reactive powder concrete (PPPRC). Wang et al. observed that severe spalling decreased as the fibre content in the samples was increased the compressive strength. They found that flexural and tensile strengths did not reduce with increased temperatures due to the PPRPC added to the concrete, which enhanced mechanical properties when compared with standard concrete. The results showed that peak bond stress, stress–slip and elastic modulus reduced when the temperature increased. The bond strength of glass FRP and basalt FRP bar samples dramatically decreased when increasing the temperature, as shown in Figure-27 [237].

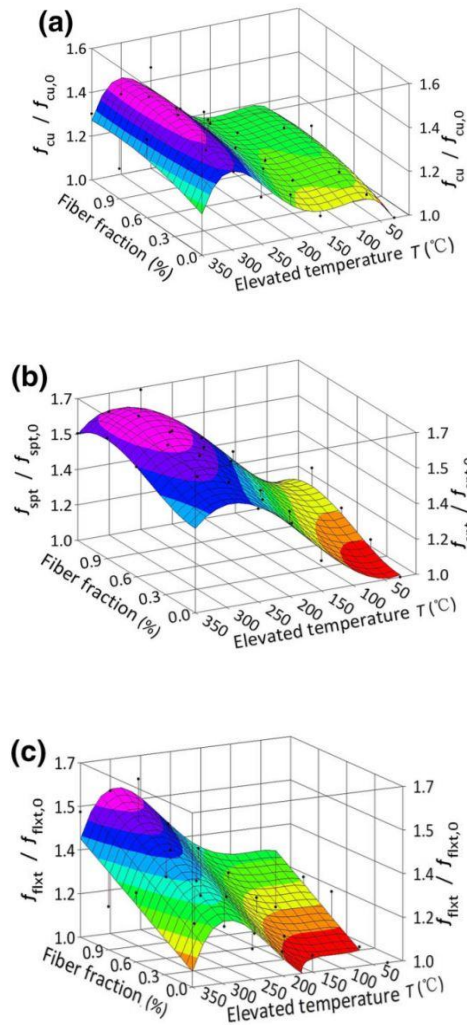


Figure 2-27 Effects of temperature on the mechanical properties of RFC at temperature [237].

According to Ozawa and Morimoto, concrete that contains fibre reduced the build-up of the vapour pressure of the water inside the concrete, and decreased the spalling of concrete exposed to high temperature [238]. The control concrete, critically dropped, and the maximum in spalling was about 7 mm. Other researchers observed FRP composites as the most convenient among the possibilities investigated, as these additions enable the best fatigue performance in comparison with concrete without FRP under exposure to high temperatures [227]. The majority of researchers have studied the impacts of high temperatures

on mechanical properties, but all constructions are exposed to thermo-mechanical and dynamic loads.

2.9 Conclusions and Current Challenges

This chapter provides an understanding about the behaviour of EFRC. The following are the key findings from a critical analysis of the existing research.

- EFRC increases tensile strength, improves ductility, shrinkage properties, impact, fatigue properties, post-cracking resistance, cavitation, toughness, and erosion resistance, and the serviceability of concrete.
- SFRC shows low maintenance costs, an expansion in load capacity, low load limits through cracks, and increased tensile strength.
- Plastic fibre reinforcements show a high estimation of flexible modules with an improvement in various mechanical properties.
- Waste fibre reinforced concrete shows an increase in load capacity and crack resistance and a rise in tensile strength with a low overall cost.
- In general, workability was shown to decrease after an increase in the number of fibres in concrete. A possible solution is to use superplasticizers to overcome reductions in workability.
- The compressive strength of a control concrete without fibre was more than with fibres.
- With an addition to the ratio of fibre in the concrete mixture, there has been notable development in the flexural strength of concrete.

To obtain the optimum values of the performance parameters, a very good mixing is necessary. However, mixing processes have their challenges, and it is important to understand them before discussing how to optimize improvement. The challenges of adding fibre to a concrete mix can, if fully addressed, provide desirable properties. However, much research remains to be done to look at these challenges and their relative impact on the resulting concrete properties. Moreover, real concrete structures normally undergo dynamic loads with a coupling of mechanical and thermal conditions. The sole aim of using fibre is to

modify the mechanical properties of concrete to increase its suitability for constructing a range of structures. A great deal of effort has been made in reinforcing concrete with different types of fibre. However, there are still various unaddressed challenges related to the optimization of the proportion of fibre, the shape of the fibre and the mixing method, and the properties achieved demand comprehensive research. In addition, the evolution of concrete reinforcement has been mainly influenced by mixing processes and methods. Hence, comprehensive research with an emphasis on the optimization of FRC, in particular to enhance its strength against thermo-mechanical dynamic loads, is still required.

3 Methodology

The above identified research gaps are addressed with a comprehensive research methodology composed of four steps. The first step focused on contextual understanding and comprehending the literature. A comprehensive literature review was conducted. The impact of different types of fibre on concrete and the key conclusions and gaps in FRC research were highlighted, together with a critical analysis of the existing literature. This achieved research objective 1, as explained in Chapter 2. Secondly, an empirical laboratory mixture was carried out to reinforce concrete with different types of fibres to different proportions. Fresh and quasi-static tests were performed to investigate the optimization of the type, ratio, and shape of fibre. These tests investigated the workability and tensile, compressive, and flexural properties after the reinforcement of the concrete with fibres. Data analysis was performed to correlate the quasi-static properties and determine the optimal fibre type, ratio, and shape. This achieved research objectives 2 and 3. In addition, objectives 2 and 3 were achieved using an experiment scheme performed in a laboratory. Thirdly, the optimized reinforcement parameters were used to develop cantilever beam specimens for dynamic thermo-mechanical load tests. A modal exciter-based experimental scheme was designed to test the mechanical behaviour of the reinforced concrete beam specimens. The measured data in respect of crack growth, optimized reinforcement parameters, and applied coupled loads were mathematically correlated. Finally, a model was developed for further validation. The final phase was to validate the developed model in line with objective 4. Specimens were tested on arbitrary values of thermo-mechanical loads. Values obtained from the model and experiments were compared and errors measured. Further model modification was performed to check if each error was within acceptable limits. This achieved research objective 5.

3.1 Materials and Mixing

3.1.1 Materials

Portland EMC II composite cement, regular fine and coarse aggregates were used in this study. The sieve analysis of the aggregates used shows that the aggregate is practical in designing the concrete mixture and the particle size distribution of the coarse and fine aggregates is presented in Figures 3-2 and 3-3. Superplasticizer (Scc) was used to increase the workability of the concrete. The Flow Aid Scc superplasticizer

was used to improve the workability of concrete. It provides good workability and flowability. Table 3-1 Specifies the requirements of the superplasticizer using in this study. With outstanding cohesion, null segregation, and low bleed water, the concrete has incredibly high levels of workability. With great cohesion, null segregation, and low bleed water, the concrete has remarkably high levels of workability [239].

Table 3-1 Specification of superplasticizer.

Main action	Concrete superplasticiser
Dosages	0.5-1.25% On cement weight
Properties Appearance	Yellow Liquid
Specific Gravity	1.10
Chloride content % w/w	Less than 0.1
PH value	4.0
Suitability of concrete	Suitable For All Portland Cements

Four types of fibres were used: Novocon® FE-1050 steel fibres; Novocon® XR-1050 steel fibres; Enduro®Fiber high-performance polymer (HPP); and Enduro® Mirage, which is 100% virgin copolymer fibre. The fibres were added to concrete in a range of percentages (0.5%, 1%, 1.5% and 2%) of different lengths (20 mm, 30 mm and 40 mm) for each type. Images of each type are presented in Figure 3-1. The properties of the different types of fibre and their suppliers are shown in Table 3-2.

Table 3-2 Properties of the fibres used in the study.

Type of fibre	Shape	Diameter (mm)	Length of fibre (mm)	Tensile strength of fibre (N/mm ²)	Supplier
SPRC-1	Straight	1.00	(20, 30, 40)	1150	Sika
SFRC-2	Crimped	1.45	(20, 30, 40)	690	Sika
PFRC-1	Macro/ Monofilament	0.95	(20, 30, 40)	465	Sika
PFRC-2	Crimped	0.92	(20, 30, 40)	552	Sika

PFTC-1



PFRC2



SFRC-1



SFRC-2



Figure 3-1 Different types of fibres used in this study.

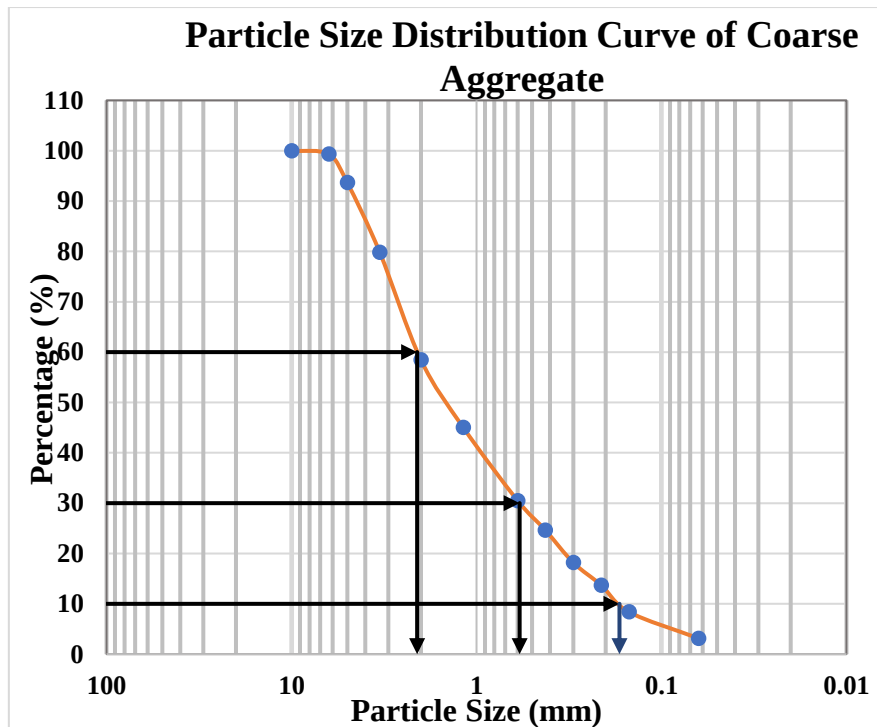


Figure 3-2 Particle size distribution of the coarse aggregate.

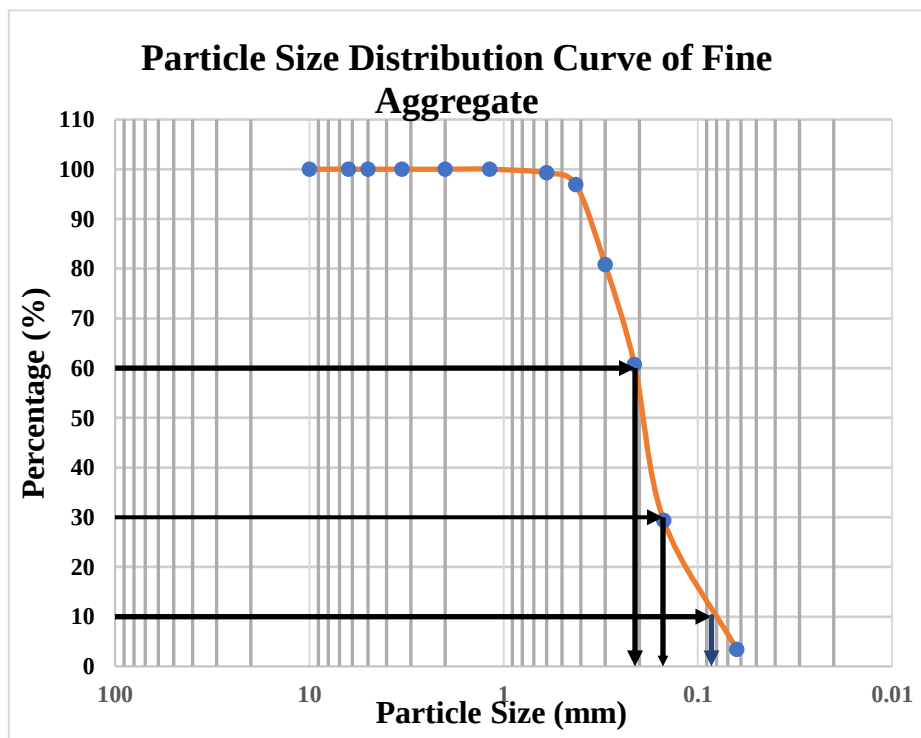


Figure 3-3 Particle size distribution of the silty sand sample 1.

3.1.2 Mixing, Casting, and Sample Preparation

A slump target in the range from 3 cm to 6 cm and a specific strength of 30 N/mm² for 28 days were set, as shown in the mixing model (see Appendix 1). The water-cement (w/c) ratio of the prepared concrete blend was 0.52. Table 3-3 provides the percentages for mixing 1 m³ of the control concrete. A one-axis horizontal mixer was used to prepare reinforced concrete mixers. This study performed 49 fibre mixes of reinforced concrete, including a control mix. For example, type-1 fibre (S1) was used to make 12 concrete mixtures using different lengths of fibre (20 mm, 30 mm, and 40 mm), each length making up a different percentage (0.5%, 1%, 1.5% and 2%) of fibres that were a replacement for the cement in the concrete mix. The test pieces were placed in water in a tank to be cured for 28 days at room temperature (20 ± 5 °C). In accordance with the “Design of Normal Concrete Mixes” produced in 1975 by the British Department of Environment (DoE)[240], the process adhered to the standard 28-day hardening requirement for concrete. Figure 3-4 shows the experimental scheme.

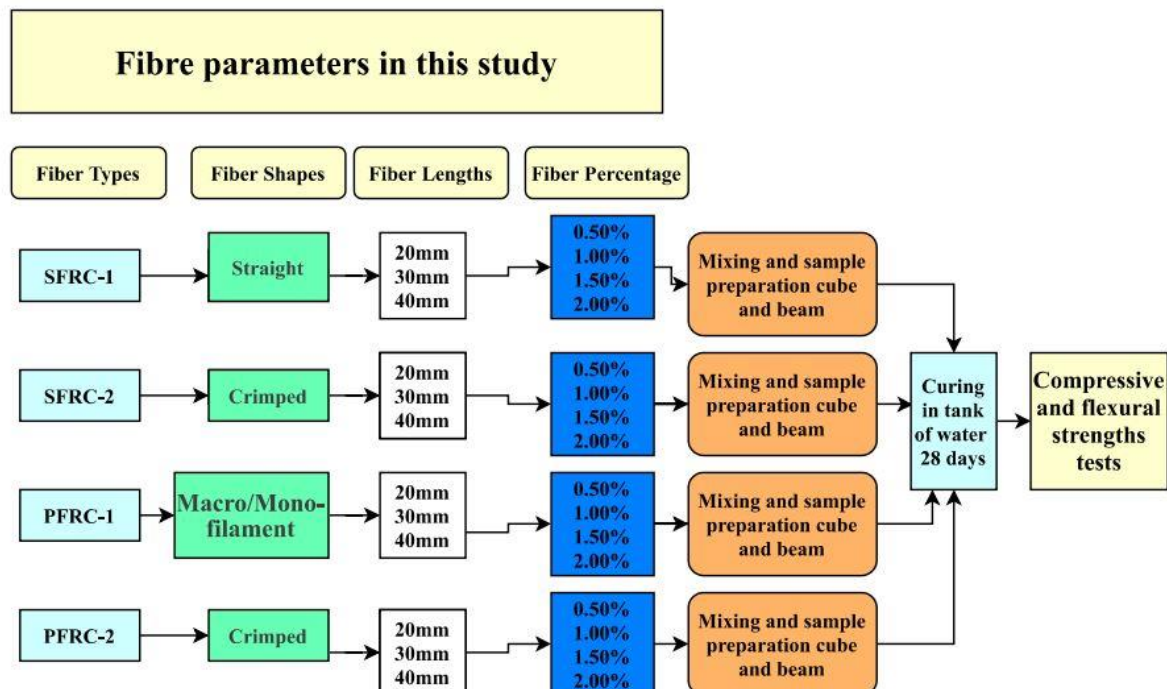


Figure 3-4 Experimental scheme.

Table 3-3 Mixing percentages of the control concrete.

Quantity	Cement (kg)	Water (kg)	Fine aggregate (kg)	Coarse aggregate (kg)
Per m3	427	213	679	1061
Trial mix 0.017 m3	7.26	3.62	11.54	18.037
Superplasticizer (0.5% form cement)	0.0363 kg for trial mix			

3.2 Testing Scheme

Fresh-state and mechanical property tests to observe the impact of FRC, including its workability and compressive, split tensile and flexural strengths, were carried out in this study. The workability test was according to BS EN 12350-2 (2009) [241]. The compression test was performed in accordance with BS EN 12390-4 (2000) [242], using cube samples with each. The compressive test was conducted on 7 days and 28 days. A Universal Hydraulic Test Machine was used to perform the compressive test using load control by a displacement of approximately 5 mm. The split tensile test was performed in accordance with BS EN 12390-6 (2009) [243], using cylinder samples with each mixture. The split tensile strength test was conducted on 28 days. The split tensile strength test was performed by using a displacement load control of approximately 5 mm. The flexural strength test was performed in line with BS EN 12390-6 (2009) [243], using three bending moments. Beam samples with each mixture were the sample produced in the size 100*100*400. The flexural strength test was conducted on 28 days. The flexural strength test was performed by using a displacement load control of approximately 5 mm. Figure 3-5 shows the machines used in the compressive, split tensile and flexural strength tests.

(a) Compressive strength test

(b) Flexural strength test



(d) split tensile strength test



Figure 3-5 Mechanical tests of compressive, split tensile and flexural strengths.

3.3 Design Optimization Procedure

The study used the testing results and the cost of the FRC to develop an optimization approach for selecting the most optimal fibres to add to concrete in terms of analysing its mechanical qualities. Furthermore, studied how they affect the hardness, the effects of fibre qualities (percentage, length, and type), and from an economic standpoint. An optimization method is mainly served by determining a performance criterion for the decision, whereby dependent and independent variables influence the final decision and parameter formulation. The input parameters (types, lengths and percentages of fibres) that influenced ease of mixing and the cost of the fibres. Concrete has a considerable compression force, so to make it stronger, engineers add fibre to the internal concrete structures. Fibre enhances the concrete structure's tensile strength, developing its robust construction. Figure 3-6 is a chart showing the weighted scale-

based parametric analysis developed for the design optimization of reinforced concrete in this study. Design variables for the optimization were divided into two groups: input and output parameters. The input parameters were the influences of type, length, and percentage of fibres on the performance of concrete, including mechanical and fresh-state concrete property samples. This study Searched for the best relation between fibre dose and dimension to optimize the combined responses of workability, splitting tensile strength, flexural strength, and compressive strength. The input parameters in this study were according to the type, length and percentage of the fibres used. Cost is also used as an influencing input parameter as it can be different for different types of fibres. Fibre length and percentage were influenced by ease of mixing the fibre, especially in terms of the workability of the concrete.

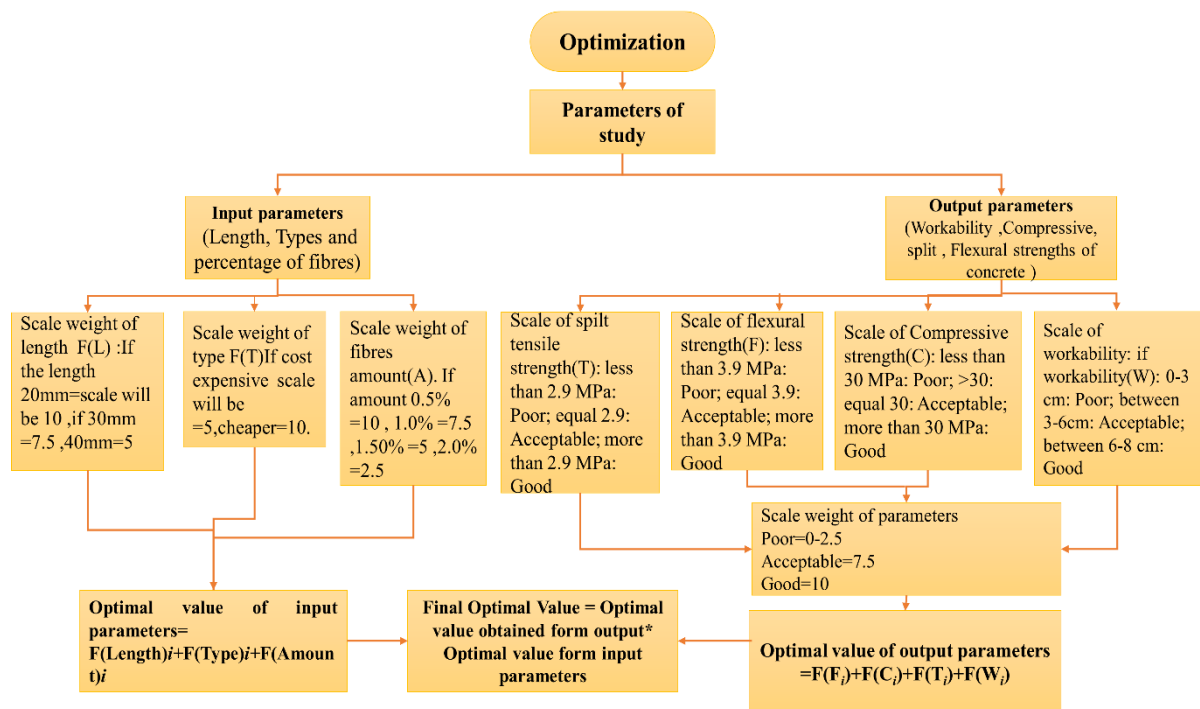


Figure 3-6 Optimization procedure.

We undertake the empirical analysis using input and out parameters and the following explain combined the parameter in this study. The highest number means highly optimized concrete.

3.3.1 Input Parameter Optimization

The Input parameters are Type, percentage, and length. The scale of fibre type **F(Type)*i*** according to Scale of Cost if cost: expensive=5: cheaper =10. The Scale of fibre length **F(Length)** according to Scale of easy to mix 20mm=10 :30mm=7.5: 40mm=5. The scale of fibre percentage **F(amount)*i*** according to Scale of quantity of fibre 0.5% =10: 1% =7.5: 1.5% =5: 2%=2.5. After obtained the scale infancies number will combined the scales for input parameters to calculate the Optimization number of input parameters as shown in equation 3-1.

$$\text{Optimization number of input parameters (i) = (Type scale + length scale + percentage scale)} \quad (3-1)$$

3.3.2 Output Parameter Optimization

The output parameters are including workability, compressive strength, split tensile strength, and flexural strength, which influenced by the scale, the following are explain these scales.

- The scale of workability had three different values depending on slump test value: if the slump: 0-3 cm is Poor; between 3-6cm is acceptable; between 6-8 cm is good. The weight scale of workability will be 2.5 for poor, 7.5 for acceptable and 10 if good. the equation 3-2 illustrates the workability scale value.

$$F(Wi) = \text{weight scale of workability} \times \text{workability value obtained from test} \quad (3-2)$$

- The scale of compressive strength had three different values depending on results of compressive test if compressive: less than 30 MPa: Poor; > 30: equal 30: ok; more than 30 MPa: Good. Where the 30 MPa is the target compressive for mix design. The weight scale of compressive will be 2.5 for poor, 7.5 for acceptable and 10 if good. the equation-3 illustrates the compressive scale.

$$F(Ci) = \text{weight of requirement} \times \text{Compressive strength value obtained from test} \quad (3-3)$$

The scale of split tensile strength had three different values depending on results of tensile test if tensile: less than 2.9 MPa: Poor; equal 2.9: ok; more than 2.9 MPa: Good. The weight scale of split tensile will be 2.5 for poor, 7.5 for acceptable and 10 if good. the equation 3-4 illustrates the tensile scale.

$$F(Ti) = \text{weight of requirement} \times \text{Tensile strength value obtained from test} \quad (3-4)$$

- The scale of flexural strength had three different values depending on results of flexural test if tensile if flexural: less than 2.9 MPa: Poor; equal 2.9: ok; more than 2.9 MPa: Good. The weight scale of split tensile will be 2.5 for poor, 7.5 for acceptable and 10 if good. The equation 3-5 illustrates the flexural scale.

$$F(Fi) = \text{weight of requirement} \times \text{Flexural strength value obtained from test} \quad (3-5)$$

- After calculating the scale influences for each parameter will be combined these equations to calculate the optimization number of output parameters as illustrated in equation 3-6. the highest number means highly optimized concrete.

$$\text{Optimization number of output parameters} = F(Wi) + F(Ci) + F(Ti) + F(Fi) \quad (3-6)$$

$$\begin{aligned}
& \textbf{Final optimization number} & (3-7) \\
& = \text{number of effects of input parameters on optimization} \\
& \times \text{output optimization number}
\end{aligned}$$

3.4 Pre-processing the Data for the Empirical Model

3.4.1 Multiple Linear Regression Method

Identifying the relationship between two or more variables is a common task in engineering. Using statistical regression aids in forming mathematical equations for observable phenomena, and MLR is widely used to express the relationship between several independent variables and a dependent variable. The dependent variable, which has multiple equivalent coefficients, is determined by the number of parameters [244,245]. When there are more than two independent variables, multiple regression is performed. MLR evaluates the relationship between two or more input variables by adapting a linear equation to the observed data [246,247]. Regression analysis can be used to estimate the relationship between the variables. Modelling and analysing one dependent variable and one or more independent variables are the mainstays of this technique [248]. The goal of regression is to minimize the difference between experimental and predicted results using the principle of least squares [249]. The procedure entails selecting an appropriate initial form for the equation that closely resembles the correlation between the independent and dependent variables. An MLR model was used to explore and compare the effect of the input parameters (i.e., the type, shape, length, and percentage of fibres) on the mechanical properties of concrete, as indicated in Equation (1) [250].

$$\hat{Y} = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 \quad (3-8)$$

Where, X_1 indicates the type, X_2 represents the shape, X_3 represents the length, X_4 represents the percentage of fibres, and b_0 is the predicted regression coefficient that represents the association between the dependent variable $\hat{Y}$ and parameters X . The current work proposes a Khan Khalel model that can predict the desirable compressive and flexural strengths for any given values of key fibre parameters. The Khan Khalel

model used four dependent parameters to predict the compressive and flexural strengths of FRC` according to the fibre. The second parameter is shape, as the value of tensile strength differs for the different fibre shapes for the same type of fibre. The third parameter is the percentage of fibres, whereby four different proportions were used in this study: 0.5%, 1%, 1.5%, and 2%. Finally, the fourth parameter, length, was assessed according to three lengths: 20 mm, 30 mm, and 40 mm as shown in Table 3-2. To eliminate the influence of variances in properties, such as dimension and order of importance between variables, the input parameters for the FRC were transformed from their original values in Table 3-2 into standardized dimensionless values. This allowed the effect sizes of different variables to be compared. Matlab® multi linear regression command is used in our paper to generate the relevant coefficients for developing the proposed Khan Khalel model discussed in section 5.

3.4.2 Methods for Evaluating the Accuracy of the Prediction Model

In general, when evaluating the implementation of a prediction method, it is critical to employ a variety of assessment criteria to determine the performance of the model. In this study, four metrics are used to check the predictive accuracy: MAPE, MSE, and R². The metrics are as follows:

- Mean absolute percentage error (MAPE): this is one of the most common metrics used to measure the forecasting accuracy of a model, as shown in Eq. (3-9). The purpose of the MAPE formula is to gauge how different the measured value is from the exact value [251].

$$MAPE = (1/n) * \Sigma(| actual - forecast | / | actual |) * 100 \quad (3-9)$$

Where, Σ is sum, n is the sample size, *actual* is the actual data value, and *forecast* is the data value forecast.

- Mean squared error (MSE) is another common metric used to measure the prediction accuracy of a model [252]. MSE is calculated as shown in Eq. (3-10):

$$MSE = (1/n) * \Sigma(actual - forecast)^2 \quad (3-10)$$

Where, Σ is sum, n is the sample size, *actual* is the actual data value, and *forecast* is the data value forecast.

3.5 Identifying the Parameters of the Numerical Model

3.5.1 Description of the Numerical Model

The cube and beam geometry design procedures of the experiments given in the previous part were created in this study using Abaqus software [253]. The concrete model consisted of plain concrete (cube, beam), steel and plastic fibres, and loading/support. Embedding the fibres in the concrete region is assumed to lead to a perfect bond between the concrete and the fibres. It is worth mentioning that slipping behaviours have the same bond idea for both beam and cube. Despite this, the perfect bonding assumption has been widely utilized in the literature for concrete-like structures [254,255].

The concrete damage plasticity model (CDPM) is a constitutive model that can be used to predict the behaviour of concrete in numerical approach. It describes the constitutive behaviour of concrete based on the introduction of scalar damage variables. The four main components of the CDPM are: damage evolution, yield criterion, law of hardening/softening, and flow rule. CDPM characterizes the compressive and tensile responses of concrete. The overall strain, ε , can be split into two components according to the standard elastic-plasticity theory to reflect concrete nonlinearity and irreversible deformation, as shown in Eq. (3-11). The CDPM includes a scalar damage variable, d , $0 \leq d \leq 1$, and uniaxial compressive/tensile damage variables, d_c and d_t , for simulating progressive material deterioration, as shown in Eq. (3-12). (3-13), (3-14) and Eq. (3-15).

$$\varepsilon = \varepsilon^{el} + \varepsilon^{pl} \quad (3-11)$$

$$\sigma_{ij} = (1 - d)D_{ijkl}^{el}(\varepsilon_{ij} - \varepsilon_{ij}^{pl}) \quad (3-12)$$

$$\sigma_c = (1 - d_c)E_0(\varepsilon_c - \varepsilon_c^{pl}) \quad (3-13)$$

$$\sigma_t = (1 - d_t)E_0(\varepsilon_t - \varepsilon_t^{pl}) \quad (3-14)$$

while it is given for uniaxial cyclic loading conditions as

$$d = 1 - (1 - s_t d_c)(1 - s_c d_t) \quad (3-15)$$

The yield surface specifies the crucial stress level at which plastic deformation is predicted to begin. Many yield criteria have been proposed to account for strength evolution under tension and compression. The CDPM finally adopted the classic criterion first proposed by Lubliner et al. [256] and then refined by Lee and Fenves [257].

$$F = \frac{1}{1-\alpha}(\bar{q} - 3\alpha\bar{p} + \beta(\varepsilon^{pl})\langle\bar{\sigma}_{\max}\rangle - \gamma\langle-\bar{\sigma}_{\max}\rangle) - \bar{\sigma}_c(\varepsilon_c^{pl}) = 0 \quad (3-16)$$

$$\alpha = \frac{(\sigma_{b0}/\sigma_{c0})-1}{2(\sigma_{b0}/\sigma_{c0})-1}; \beta = \frac{\sigma_{c0}(\varepsilon_c^{pl})}{\sigma_{t0}(\varepsilon_t^{pl})}(1 - \alpha) - (1 + \alpha) \quad (3-17)$$

$$\gamma = \frac{3(1-K_c)}{2K_c-1}$$

The hardening law describes the pre-peak behaviour when the elastic area ends, whereas the softening law covers the post-peak behaviour throughout the plastic flow [258]. Anisotropic hardening is considered in Abaqus, as shown in the analogous plastic drives as well as the strain evolution law, as shown in Eq. (3-16) and Eq. (3-17).

$$\varepsilon_c^{in} = \varepsilon_c - \sigma_c/E_0 \quad (3-18)$$

$$\varepsilon_t^{ck} = \varepsilon_t - \sigma_t/E_0 \quad (3-19)$$

The compressive and tensile inelastic strains are ε_c^{in} and ε_t^{ck} , respectively. Plastic deformation is determined by the flow rule, which is guided by a potential flow function as shown in Eq. (3-18) and Eq. (3-19). The CDPM uses a non-associated possible flow rule due to the variations between metal and non-metal materials, and the possible function, G , has a hyperbolic Drucker-Prager type form, as shown in Eq. (3-20), Eq. (3-21) and Eq. (3-22):

$$\varepsilon_c^{pl} = \varepsilon_c^{in} - \frac{d_c}{(1-d_c)} \frac{\sigma_c}{E_0} \quad (3-20)$$

$$\varepsilon_t^{pl} = \varepsilon_t^{ck} - \frac{d_t}{(1-d_t)} \frac{\sigma_t}{E_0} \quad (3-21)$$

$$G = \sqrt{(e\sigma_{t0}\tan \psi)^2 + \bar{q}^2} - \bar{p}\tan \psi = 0 \quad (3-22)$$

The CDPM in Abaqus is utilized in this study to describe compressive strength in normal concrete, assuming that the fibres are randomly distributed in the matrix and the FRC is thus considered as a homogeneous material. The default settings of the model parameters defining its operation in a complex stress state (ψ, f, e, Kc) [259] were used for the numerical analysis of FRC beams and cubes, and are shown in Table 3-4. According to the standard [260], the Poisson's ratio of uncracked concrete is supposed to be 0.2. Tables 3-4 and 3-5 present a representative summary of the

concrete characteristics of the Abaqus software, as described by Shin et al. [261]. The effects on FRC were carefully monitored and minimized in this research using concrete damage plasticity DCP models to obtain quasi-static behaviours from the Standard-Explicit model simulation. Readers are urged to look up comprehensive discussions on quasi-static simulations using the Standard-Explicit model in the literature [262–264]. A fixed boundary condition (BC) was used at the bottom of the cube surface, with vertical displacement defined at the top. The BCs of the experiment were simplified by employing a 50 mm diameter supporting and loading cell, as shown in Figure 3-7. A fixed BC was used for the beam sample at the bottom of the supporting cell, with vertical displacement defined at the top of the loading bars. As the finite element (FE) simulations were run using the Standard-Explicit model, the vertical displacement was applied smoothly and slowly to minimize any noticeable load effects. The function "`*AMPLITUDE, DEFINITION = SMOOTH STEP`" was utilized to enforce the smooth and slow displacement BC. The bulk viscosity option was chosen to limit the load effects on the numerical results [253]. The constitutive plasticity rule was used to model the nonlinear, elastic behaviour (containing four different fibre shapes) of the steel and plastic fibres. The plasticity model assumed that steel and plastic fibres behaved similarly to the steel reinforcement behaviour used in the literature [254,265]. Digimat-FE software was used for the composite materials to obtain the random distribution of fibres inside the concrete samples [266]. The fibre distribution and interaction between fibres and concrete are shown in Figure 3-8. The small yellow square is shown the interaction between load and support cells with the surface, and the small yellow circle is the interaction between fibre and concrete as shown in Figure 3-8. Tensile tests, comprising elastic modulus, stress, and strain, were used to provide the inputs for the plasticity model. The plasticity properties of the fibres are shown in Table 3-6.

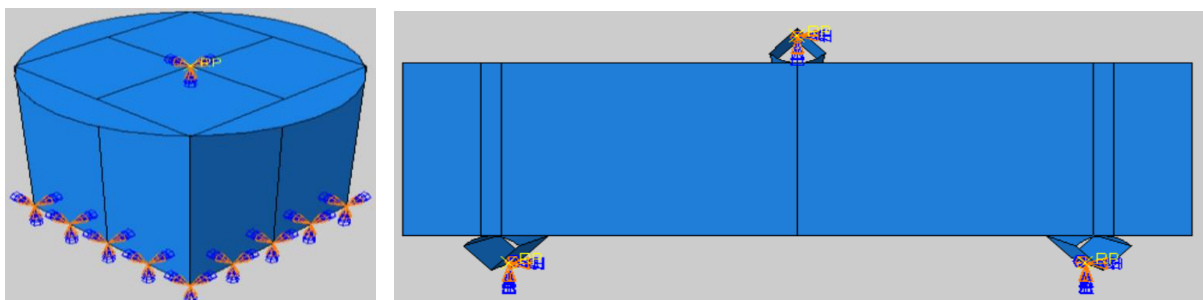


Figure 3-7 Boundary conditions of the beam and cube.

Table 3-4 Parameters of concrete damage plasticity properties.

Dilation angle	Eccentricity	f_{b0}/f_{c0}	K	Viscosity parameter
36°	0.1	1.16	0.67	0

Table 3-5 Concrete compressive and tensile behaviour.

Young's modulus MPa	34984	Poisson's ratio	0.2
Compression behaviour		Concrete compression damage	
Stress (MPa)	Inelastic strain	Damage parameter	Inelastic strain
16	0.000622996	0	0.000622996
20.01	0.000754057	0	0.000754057
24.00	0.014082286	0	0.014082286
28.01	0.015187781	0	0.015187781
32.02	0.015835257	0	0.015835257
36.00	0.017157429	0	0.017157429
38.93	0.020001589	0	0.020001589
38.72	0.021137714	0.005506698	0.021137714
35.89	0.022408446	0.078080053	0.022408446
26.70	0.024503275	0.314350292	0.024503275
15.60	0.028024185	0.599235637	0.028024185
7.79	0.033283509	0.799991781	0.033283509
Tensile behaviour		Concrete tension damage	
Stress (MPa)	Cracking strain	Damage parameter	Cracking strain
4.3678205	0.00014	0	0.00014
2.9118803	0.00042	0.333333333	0.00042
1.6379327	0.0008225	0.625	0.0008225
0.7279701	0.00147	0.833333333	0.00147

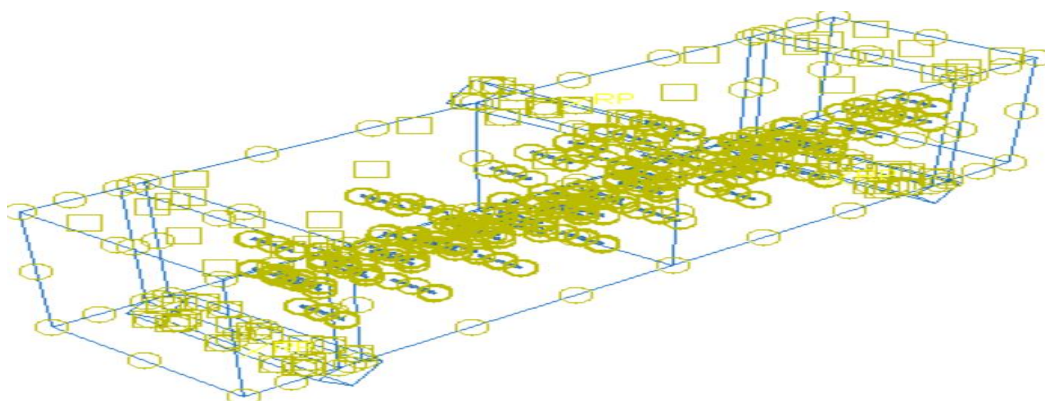


Figure 3-8 Distribution and interaction between fibres and concrete.

Table 3-6 Properties of steel and plastic fibres.

Plastic fibres		Steel fibres	
Young's modulus MPa	800	Young's modulus MPa	200000
Poisson's ratio	0.33	Poisson's ratio	0.3
Stress MPa	Strain	Stress MPa	Strain
5.26	0.000064	98	0
20.00	0.000254	195	0.0214844
60.01	0.00073	309	0.022461
100.13	0.001218	407	0.0234376
160.14	0.001948	505	0.0385742
200.10	0.002434	602	0.0551758
240.05	0.00292	716	0.0703126
274	0.003332	798	0.083496

3.5.2 Concrete Mesh Convergence Analysis

The process of mesh convergence entails reducing the element size and analysing the effect of this reduction on the solution's precision. The smaller the mesh size, the more precise the solution, as the behaviour of the design or product is sampled more precisely across its physical domain. The accuracy of numerical results is generally highly dependent on the mesh size utilized in the numerical model. More accurate results can be produced using a smaller mesh size, but this is more computationally expensive and requires greater computer capacity. The smallest mesh dimension is

not viable for the CDPM due to software and computer limitations. As a result, performing a mesh convergence study to identify the ideal mesh size is critical. Four concrete cubes with varying mesh sizes (10 mm, 8 mm, 6 mm, 4 mm, and 3 mm) were utilized in the CDPM for the mesh convergence analysis to establish the ideal element size of the concrete model. The conductivity signatures derived from the four concrete cubes are compared in Figure 3-9. The results reveal a considerable difference in conductance mesh size between the 10 mm, 8 mm, and 6 mm elements. However, the difference between the 4 mm and 3 mm elements is relatively modest. In this study, a mesh size of 5 mm was employed to represent the concrete cube for concrete disaster response assessments, when considering process time and computer memory. The same mesh convergence analysis steps were performed for the four beam sizes for flexural strength, as shown in Figure 3-10.

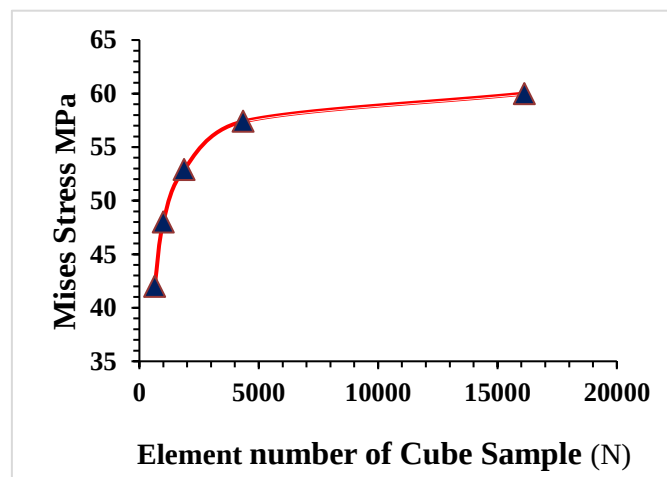


Figure 3-9 Mesh convergence analysis of FRC cube.

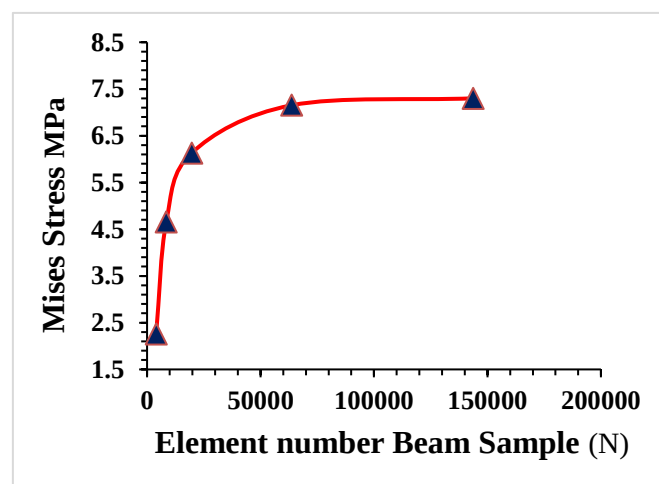


Figure 3-10 Mesh convergence analysis of FRC beam.



Figure 3-12 Beam sample preparation.

3.6.3 Dynamic Response Testing

The experimental design was similar to approaches used in previous studies [267]. The first seeded crack SFRC sample was set on a Data Physics V55 shaker (Hailsham, UK). The signal generator produced a sine output signal, which sent the signal to the shaker. A mica band heater was used throughout the trials to transmit a temperature load to the samples. An accelerometer was attached to the free end of the beam to monitor the acceleration in real time. The acceleration and time data were recorded on Signal Express software using a DAQ NI 9174 chassis and a DAQ NI 9234 card (Figure 3-13). Appendix 3 explains the sensitivity and reliability of the used accelerometer in this study.

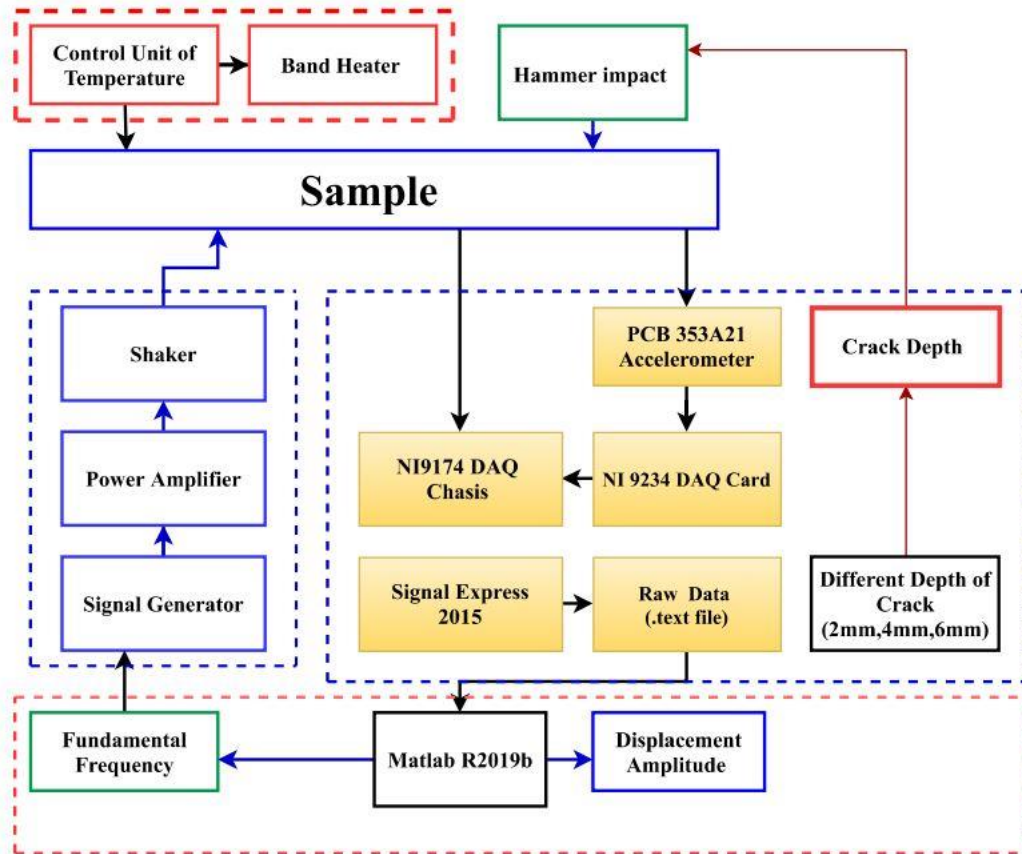


Figure 3-13 Experimental procedures [adapted from reference][268].

The experiment was performed in stages. First, the fundamental natural frequency of the specimen was determined three times using impact tests. The average number of the frequency response was then calculated. Second, the shaker generated a sinusoidal motion with a displacement amplitude of 1 mm at the measured fundamental frequency. Finally, the shaker powered the beam and vibrated at the frequency, producing the first maximum beam displacement amplitude. The displacement amplitude was calculated and used to investigate the crack. Figure 3-15 illustrates a seeded crack depth ranging from 2 mm to 6 mm of the CFRC beam. Continuous force vibration caused the depth of the crack, reducing the local rigidity of the crack location and modifying the dynamic response characteristics of the entire system. When the displacement amplitude displayed in real time by the Signal Express program was drastically lowered, the experiment was paused. Next, the fundamental frequency of the system was measured and re-entered. As a result, the experiment was re-started. The methods were used for all seeded crack beams. Figure 3 above shows the experimental steps and Figure 3-14 below presents the experimental setup.

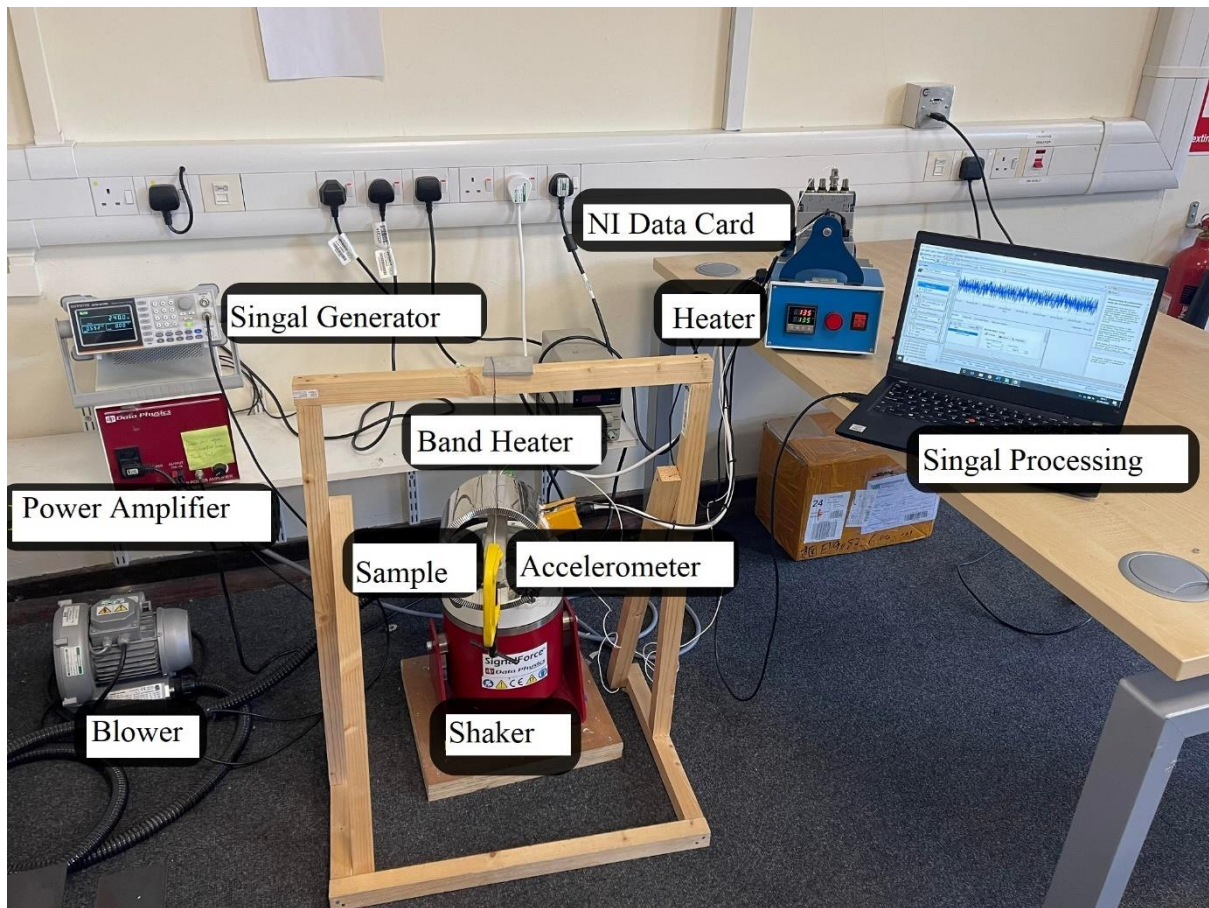


Figure 3-14 Experimental setup.

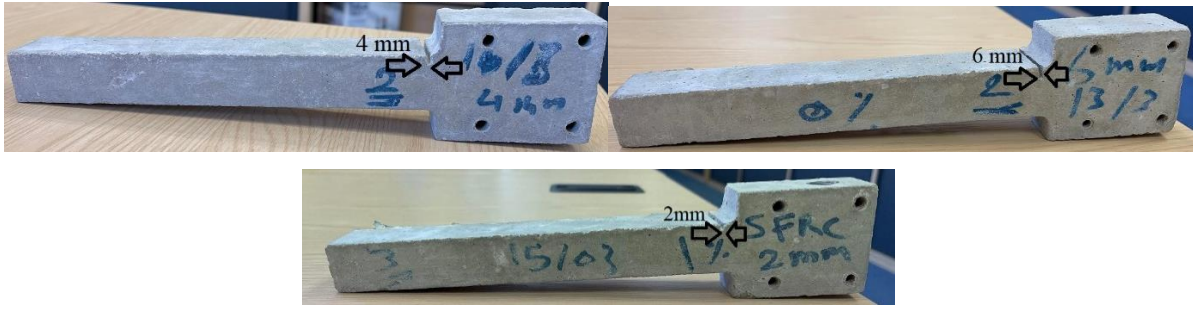


Figure 3-15 Illustrates a seeded crack depth ranging from 2 mm to 6 mm of an SFRC beam.

3.6.4 Calculation of the Stress Intensity Factor

The stress intensity factor is the driving force that drives the crack to grow. This study considers the load applied as the ultimate load (F) at the beam ends to generate the worst deflection situation. The resulting maximum load can be calculated as follows: Max deflection equals the specified amplitude value at resonance. Therefore, Eq (3-23) amplitude value can be used to determine the load. As a result, the ultimate load at the crack's tip will have a sine wave-like shape with angles between 0 and 360 degrees.

$$\delta_{max} = \frac{PL^3}{3EI} \quad (3-23)$$

$$\sigma = \frac{M}{Z} \quad (3-24)$$

Where M is the bending moment, σ Stress at the tip and Z is the section modulus, calculated as.

$$Z = \frac{b \cdot h^2}{6} \quad (3-25)$$

Where b=30 mm and h=25 mm are the cross sections of the cantilever beam in this study.

The minimum and maximum stress values can be provided $\Delta\sigma$ by the load sine graph, which enables it to supply the value needed for ΔK .

$$\Delta K = Y \Delta\sigma (\pi \times \text{crack depth})^{0.5} \quad (3-26)$$

From the literature can be calculated Y for mode-1 fracture under bending load specimens. It will be roughly equal to 1.12. Crack depth values are available based on the amplitude value chosen in Eq. (3-23).

3.7 Analytical Model to Calculate the Natural Frequency during Different Crack Depths

Fundamental frequency, displacement amplitude, and mode shapes are all ways to express a dynamic structural response. This study covers the first two techniques. Ultimately, measuring frequency and structural displacement amplitude is easier and more convenient than monitoring the mode forms in real construction circumstances. The first mode shape is seen in many real structural applications and is primarily responsible for any structural property changes due to its high energy content.

3.7.1 Abstraction of Good Working Conditions of the Samples in this Study

There are various structures within practical real application scenarios. A cantilevered beam structure was studied because, as with most previous research, a cantilevered beam is an essential element in real engineering applications. After all, it can resist high mechanical loads. Therefore, bridged and concrete applications may be considered cantilever beams. In addition, the dynamic response of a cantilever beam is more violent when it is exciting.

Figure 3-11 above shows how the cantilever beam in this study was constructed. The beam can be excited by vibrating movement from the fixed left end. To model crack damage in functional structures, the initial seeded crack was on the top surface and close to the stationary end of the beam. There was one crack location. To depict damage in real life, the distance between the beam's start and the fixed end is 200 mm. Furthermore, an additional mass on the free beam end represents an accelerometer in contrast to a practical application. It clamps a mass of 0.6 g and 670 g, respectively, used in later experiments in the research.

3.7.2 Modelling Crack Size

Cracks alter the local stiffness of a structure. A large crack depth reduces local stiffness significantly. As illustrated in Figure 3-16, a crack in a beam can be represented by a torsional spring. Ostachowicz and Krawczuk used Equations (3-27) and (3-28) to model the torsion spring stiffness related to an open single-sided crack on a beam [269].

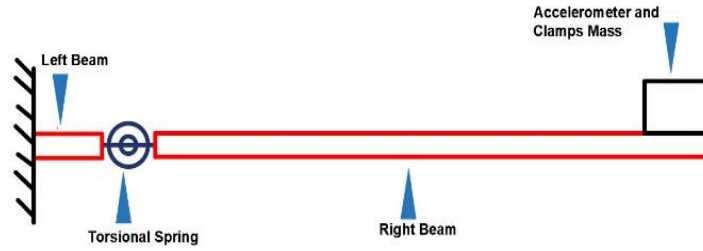


Figure 3-16 Torsion springs–cantilever beams–accelerometer system[268].

$$k = \frac{EbH^2}{72\pi f_r\left(\frac{a}{H}\right)} \quad (3-27)$$

$$f_r\left(\frac{a}{H}\right) = 0.6384\left(\frac{a}{H}\right)^2 - 1.035\left(\frac{a}{H}\right)^3 + 3.7201\left(\frac{a}{H}\right)^4 - 5.1773\left(\frac{a}{H}\right)^5 + 7.553\left(\frac{a}{H}\right)^6 - 7.3324\left(\frac{a}{H}\right)^7 + 2.4909\left(\frac{a}{H}\right)^8 \quad (3-28)$$

Several previous studies used a similar model of spring stiffness derived from fracture mechanics to study the dynamic behaviour of beam fractures [270–277][278][279][280][281].

They employed Equations (3-27) and (3-28) directly to investigate the relationship between crack depth and spring stiffness. Their analysis assumed that bending stress was equivalent to stress on the crack upon the beam surface because of the moment constant. The estimated stiffness equations above are, however, only applicable to cracks near the surface. With greater crack propagation depths, this hypothesis may

result in spring stiffness inaccuracies. As a result, a mathematical change was introduced into Equation (3-27), as shown in Equation (3-29):

$$k = \left(\frac{H - a}{H} \right) \times \frac{E_T b H^2}{72 \pi f_r \left(\frac{a}{H} \right)} \quad (3-29)$$

The additional term $(H - a)/H$ ensures that the stiffness of the spring tends to zero as the crack depth considers the beam thickness, which relates to the actual condition. The contrast between the originally modelled and the modified stiffness is shown in Figure 3-16. A higher temperature caused a reduction in the elastic modulus, E_T , and, in due course, caused a decrease in natural frequency [282]. Equation (3-30) introduces E_T , which is a temperature-dependent value in Equation (3-31).

$$E = E_{20} * (1.06 - 0.003 * T) \quad (3-30)$$

3.7.3 Natural Frequency of the System

With the revised torsional spring model in Equation (3), a cracked beam is shown as two separate whole beams, as shown in Figure 3-17 below, consistent with other studies [270,271,284–293,273,294–303,276,304–313,277–281,283], Euler-Bernoulli classical beam theory was employed separately for the left and right beams. Thermal expansion owing to thermal loads (high ambient temperature) does not introduce force and timing since the beam has just one fixed end, on the left. The damping effect of the beam is examined because only the basic frequency of the beam is determined. For both beams, the determining variance equation can be written as Equations (3-31) and (3-32):

$$E_T I \frac{\partial^4 y_L(x, t)}{\partial x^4} + \rho A \frac{\partial^2 y_L(x, t)}{\partial t^2} = 0 \quad (3-31)$$

$$E_T I \frac{\partial^4 y_R(x, t)}{\partial x^4} + \rho A \frac{\partial^2 y_R(x, t)}{\partial t^2} = 0 \quad (3-32)$$

$$I = \frac{bH^3}{12} \quad A = bH$$

Thermal load variations have an effect on the value of the elastic modulus of the E_T material [268]. The boundary conditions of the two beams can be given as follows:

1. There is no rotation at the fixed end of the beam and, consequently,
 $\partial y_L(0, t)/\partial x = 0$.
2. There is no displacement at the fixed end of the beam and, consequently,
 $y_L(0, t) = 0$.
3. Deflection appears at the spring position, hence $y_L(l, t) = y_R(l, t)$.
4. Angular divergence due to spring rotation happens and, consequently,
 $\partial y_R(l, t)/\partial x - \partial y_L(l, t)/\partial x = (E_T I/k)[\partial^2 y_R(l, t)/\partial x^2]$.
5. The bending moment occurs in the spring position and, therefore,
 $\partial^2 y_L(l, t)/\partial x^2 = \partial^2 y_R(l, t)/\partial x^2$.
6. Shearing force occurs in the spring position and, therefore, $\partial^3 y_L(l, t)/\partial x^3 = \partial^3 y_R(l, t)/\partial x^3$.
7. There is no bending moment in the free end of the beam and, consequently,
 $E_T I[\partial^2 y_R(L, t)/\partial x^2] + J_z[\partial^3 y_R(L, t)/\partial t^2 \partial x] = 0$. J_z is ignored since it is too small.
8. There is no shearing force at the free tip of the beam and, consequently,

$$E_T I[\partial^3 y_R(L, t)/\partial x^3] - m[\partial^2 y_R(L, t)/\partial t^2] = 0.$$

The overall solution of Equation (3-32) is

$$y(x, t) = Y(x) \sin(\omega t) \quad (3-33)$$

Equation (10) is obtained by substituting Equation (12) into Equation (13):

$$\frac{d^4 Y(x)}{dx^4} - \beta^4 Y(x) = 0 \quad (3-34)$$

$$\beta^4 = \frac{\omega^2 \rho A}{E_T I}$$

The general solutions of Equation (3-30) for the left and right beams are presented as Equation (3-35):

$$Y_L(x) = A_L \sin(\beta x) + B_L \cos(\beta x) + C_L \sinh(\beta x) + D_L \cosh(\beta x) \quad (3-35)$$

$$Y_R(x) = A_R \sin(\beta x) + B_R \cos(\beta x) + C_R \sinh(\beta x) + D_R \cosh(\beta x)$$

In the boundary conditions, the general solution shown in Equation (3-35) is used. According to Cramer's rule, the characteristic Equation (3-32) is produced since at least one constant from A_L to D_R has non-zero solutions.

The equation is used to calculate the value of Equation (3-36). Next, the different orders of the natural frequencies for the cracked beam with an end mass are computed using Equation (3-34).

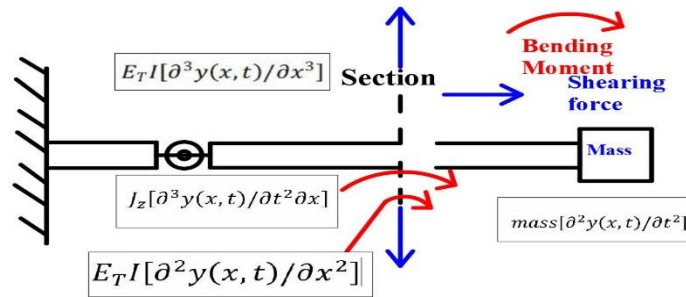


Figure 3-17 Beam cross-section free body diagram[268].

$$\begin{vmatrix}
1 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 1 & 0 & 0 & 0 \\
\sin(\beta l) & \cos(\beta l) & \sinh(\beta l) & \cosh(\beta l) & -\sin(\beta l) & -\cos(\beta l) & -\sinh(\beta l) \\
-\cos(\beta l) & \sin(\beta l) & -\cosh(\beta l) & -\sinh(\beta l) & \cos(\beta l) + \frac{E_T I}{k} \beta \sin(\beta l) & -\sin(\beta l) + \frac{E_T I}{k} \beta \cos(\beta l) & \cosh(\beta l_L) - \frac{E_T I}{k} \beta \sinh(\beta l) \\
-\sin(\beta l) & -\cos(\beta l) & \sinh(\beta l) & \cosh(\beta l) & \sin(\beta l) & \cos(\beta l) & -\sinh(\beta l_L) \\
-\cos(\beta l) & \sin(\beta l) & \cosh(\beta l) & \sinh(\beta l) & \cos(\beta l) & -\sin(\beta l) & -\cosh(\beta l) \\
0 & 0 & 0 & 0 & -\sin(\beta L) & -\cos(\beta L) & \sinh(\beta L) \\
0 & 0 & 0 & 0 & -\cos(\beta L) + \frac{m_{acc} \beta}{\rho A} \sin(\beta L) & \sin(\beta L) + \frac{m_{acc} \beta}{\rho A} \cos(\beta L) & \cosh(\beta L) + \frac{m_{acc} \beta}{\rho A} \sinh(\beta L)
\end{vmatrix}
= 0$$

(3-36)

3.8 Conclusions

This chapter provided an overview of the different techniques employed in the research that is presented later in this thesis. The reported methods were used to verify various construction applications related to FRC. Firstly, fresh and quasi-static tests were performed to investigate the optimization of fibre types, ratios, and shapes. These tests investigated the workability and tensile, compressive, and flexural properties after the reinforcement process. Data analysis was then performed to correlate the quasi-static properties and determine the optimal fibre type, ratio, and shape. The Khan Khalel model was used in the current work to predict the desirable compressive and flexural strengths for any given values of key fibre parameters. Statistical tools were used to develop and validate the model using numerical results. Thirdly, cantilever beam samples for dynamic thermo-mechanical load tests were created using the optimized reinforcement parameters. Crack growth measurements, optimized reinforcement parameters, and the coupled loads applied were mathematically correlated. Finally, a model was created for additional validation. Specimens were tested under arbitrary thermo-mechanical loads. The model and experiment values were compared, and errors calculated. A further model modification was carried out to determine whether the errors were within acceptable limits.

4 Optimization and Experiments for Testing the Mechanical Properties of FRC

4.1 Introduction

The majority of the previous researchers in this area have not considered a combination of percentages, types, and shapes of fibres in their studies in order to establish the optimal values for enhancing the properties of concrete. Analysis is still required to determine the optimum addition of fibres for desirable concrete performance. Mixing fibres has its challenges, and it is essential to consider these while deciding the optimum addition of such materials. This chapter presents the results of the parametric analysis conducted to verify the optimal shape, size, and percentage of fibres in reinforced concrete. The design variables for optimization are divided into the input and output parameters. The input parameters are the influence of type, length, and percentage of fibres on concrete performance, including samples of fresh and mechanical concrete properties. This was done in order to identify the most effective relation of fibre dose and dimension to optimize the combined responses of workability, splitting tensile strength, as well as flexural and compressive strengths. Tests were carried out on the fresh and mechanical properties of concrete reinforced with four different fibres: PFRC-1, PFRC-2, SFRC-1, and SFRC-2.

4.2 Results

4.2.1 Results of Fresh Test

Figure 4-1 provides the results of the slump test, which was conducted on 48 reinforced fibre mixtures and the control mixture. The results show that there was a gradual decrease in the workability of the concrete. It can be clearly seen that the slump in all the mixture samples with the different types of fibres was lower than for the control concrete. The results showed that the highest slump was 8 cm for the control mixture without fibre.

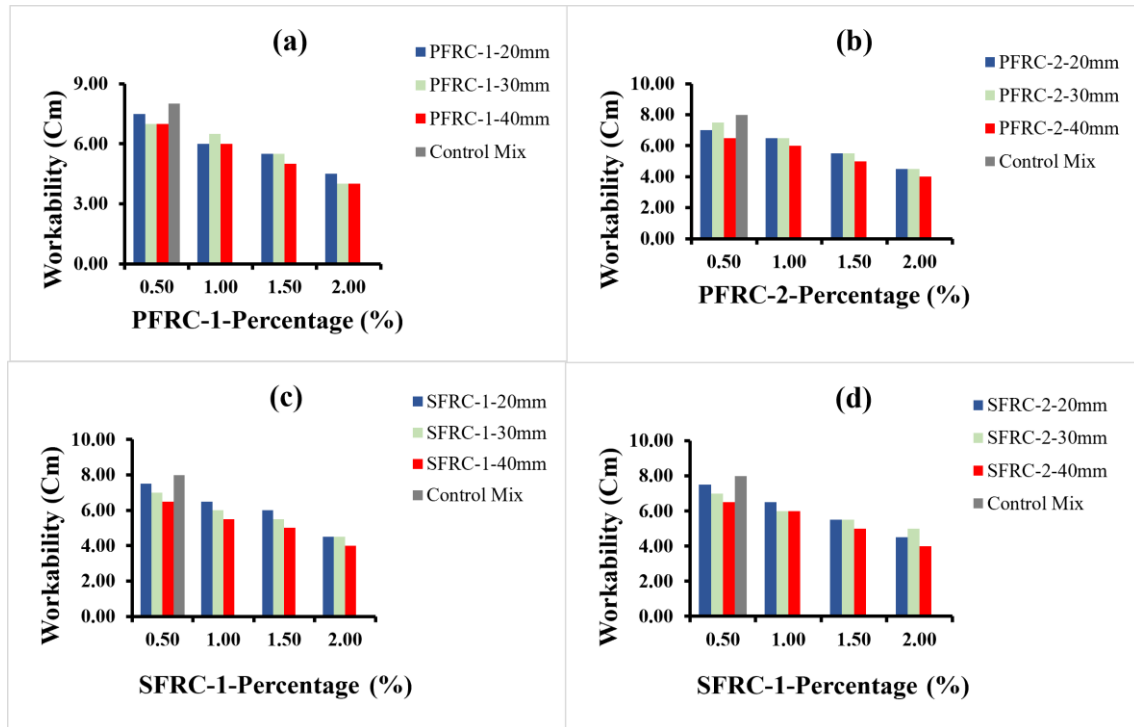


Figure 4-1 Impact of different types of fibres on concrete workability.

The lowest value in the slump test was 4 cm, which included 2% of the fibres of all types (SFRC₁, SFRC₂, PFRC₁ and PFRC₂). Figures 4-1 demonstrated the variation in slump according to the type, length, and percentage of fibre. It can be observed that there was a drop in the workability of both types but the impact of steel fibre (SFRC₁, SFRC₂) on workability was lower than that of plastic fibre (PFRC₁, PFRC₂). The length of the fibre was considered one of the reasons for the reduced workability. The results of this test show that a 20 mm length of fibre has a lower influence than lengths of 30 mm and 40 mm for steel (SFRC₁, SFRC₂) and plastic (PFRC₁, PFRC₂) fibre on fresh concrete. Thus, it is evident from the results that workability is reduced when the amount of fibre increases.

Reinforced concrete made of steel and plastic fibre shows low workability. An increase in fibre fractions led to a linear downward trend in workability diameter. However, this low workability was still in the range of the target slump (3 cm to 6 cm).

4.2.2 Mechanical Properties Tests

4.2.2.1 Compressive strength

Figures 4-2 and 4-3 demonstrate the results of the impact of fibre type, shape and percentage on the compressive strength of FRC at 7 and 28 days. There is little improvement in the compression of samples with different types of fibres, shapes and percentages. An increase was observed in the compressive strength of concrete when adding 30 mm plastic-1 fibres. However, no compressive influence was observed for lengths of 40 mm and 20 mm. There was a 10% increase in compressive resistance when the length and percentage of P1 fibres were 30 mm and 1.5%, respectively. The results indicate that the compressive strength at 28 days had decreased by about 9% when the plastic-1 fibre proportion increased.

The results demonstrate that for two lengths (20 mm and 30 mm) of plastic-2 fibre in the concrete mix, the compression strength increased slightly. However, no compression effects were seen for a length of 40 mm. When the percentage of steel fibre-1 was increased by using fibres of 20 mm, 30 mm and 40 mm to the concrete mix, the compressive strength at 7 and 28 days decreased slightly. In contrast, this low compressive was still higher than the compressive target of the concrete mixture (30 MPa), as indicated in 4-2 and 4-3. As the percentage of 40 mm steel-2 fibres increased in the concrete mixture, the compressive strength at 7 and 28 days increased slightly. However, no compressive influence was observed for lengths of 20 mm and 30 mm.

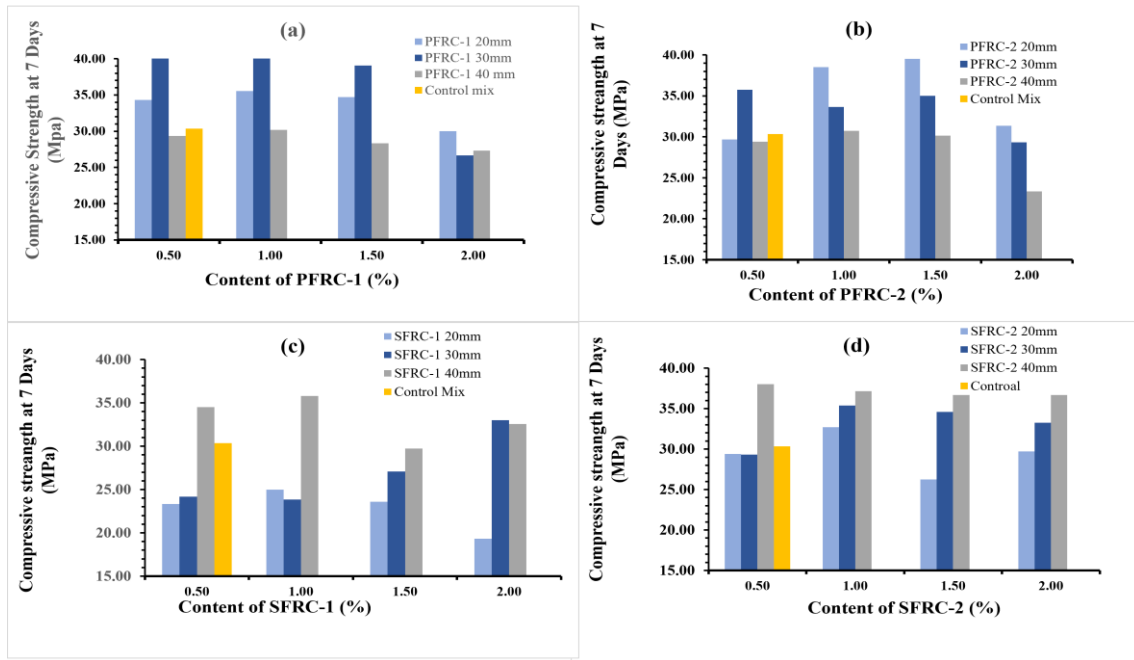


Figure 4-2 Influences of plastic-2 fibres on compressive strength of concrete at 7 and 28 days.

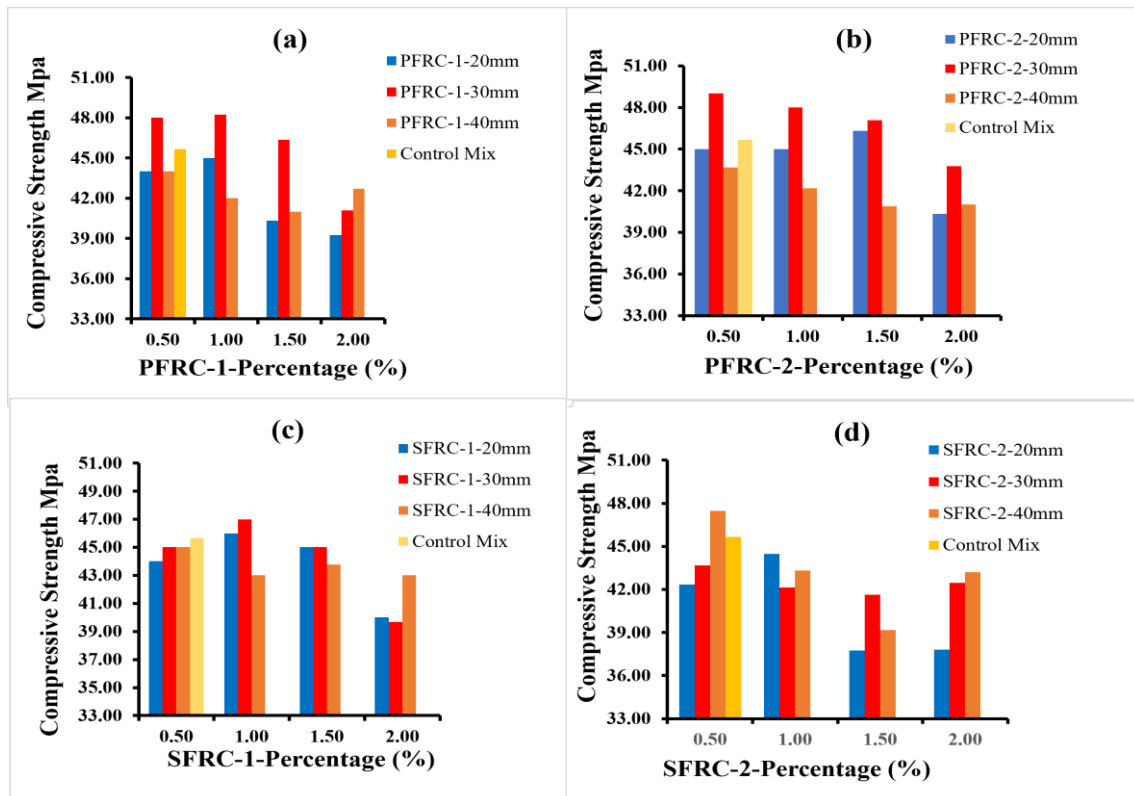


Figure 4-3 Impact of plastic-2 fibres on compressive strength of concrete at 7 and 28 days.

The results of the tests show that the FRC and the control concrete generally had similar compressive properties. The compressive strength of the FRC decreased with an increase volume fraction of the fibre for all types of fibre used in this study. For example, in comparison with the control specimen, the compressive strength of the plastic-1 fibre specimen increased slightly by adding fibre (0%, 5%) (20 mm, 30 mm) but there was a decrease in compressive strength at 40 mm of about 4%. It is clear that the enhancement in compressive strength is the same as the compressive strength of normal concrete.

It is clear that the decrease in workability of FRC increased significantly compared with the workability of normal concrete. In addition, in respect of the effect of the fibre volume fraction on the tensile properties, fibre length also has a negative impact, particularly when increasing the length, as the results showed decrease in workability.

4.2.2.2 Split tensile strength

A total of 147 cylinders of FRC samples of different lengths, shapes and percentages were tested under uniaxial stress in this study. Figure 4-4 show the influence of fibre type, shape and percentage on the 28-day tensile strength of different fibre types. There is an improvement in the tensile strength of the specimens, which is enhanced by the addition of the different types of fibres. A slight increase was observed in tensile strength for 20 mm plastic-1 fibres in the concrete mix. However, no tensile influences were seen for lengths of 30 mm and 40 mm. For plastic-2 fibres, the results demonstrate that at lengths of 20 mm, 30 mm and 40 mm in the concrete mix, the tensile strength increased slightly for 0.5% and 1.0% fibre. However, tensile strength dropped at all lengths when the amount of fibre increased to 1.5% and 2%. For SFRC-2, the results show that at lengths of 40 mm, as the proportion of fibre in the concrete mixture increased, the tensile strength increased slightly. However, for lengths of 20 mm and 30 mm, as the proportion of fibre increased, the strength of the concrete decreased.

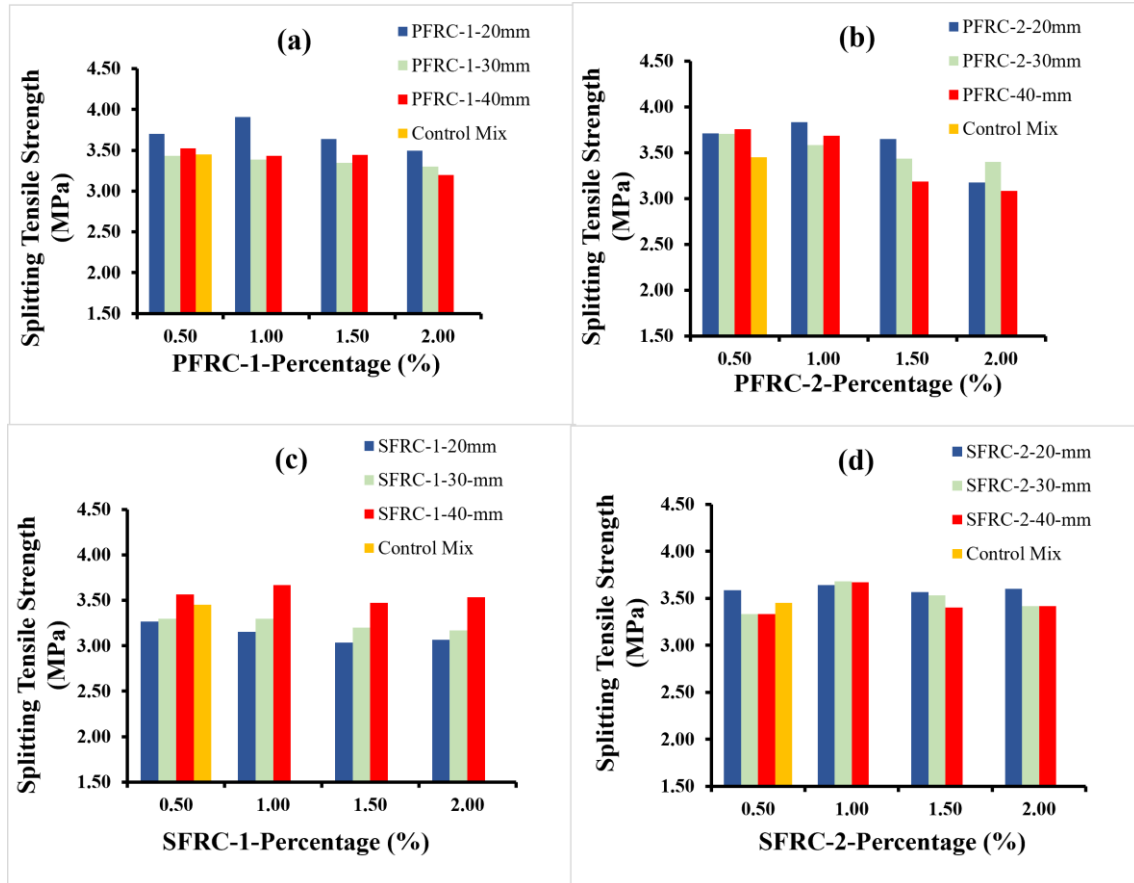


Figure 4-4 Impact of steel-2 fibres on split tensile strength of concrete.

The results of the tests showed that the FRC and the control concrete generally had similar split tensile and flexural strength properties. For instance, the tensile strength of the FRC increased with an increase in the volume fraction of the fibre for all types of fibre used in this study. In comparison with the control specimen, the tensile strength by using three different lengths (20mm, 30mm and 40mm) for each fibre: PFRC-1, PFRC-2, SFRC-1 and SFRC-2 increased by adding different percentage (11%, 3%, 0%), (11%, 4%, 7%), (3%, 5%, 5%) (5.5%, 6%, 7%), respectively as shown in Figure 4-4. It is clear that the enhancement in tensile strength of FRC increased significantly compared with the tensile strength of normal concrete. In addition, in respect of the effect of the fibre volume fraction on the tensile properties, fibre length also has a positive impact, particularly when increasing the length, as the results showed increases in tensile strength.

4.2.2.3 Flexural strength

Ninety-eight prisms of FRC samples of different lengths, shapes and percentages of fibres were tested under bending force. Figure 4-5 show the results of the impact of fibre type, shape and percentage on flexural strength at 28 days of different types of fibres. When increasing the percentage of lengths of 20 mm, 30 mm and 40 mm of plastic-1 fibre in the concrete mix, the flexural strength increased slightly with the increased fibre amount. Plastic-2 FRC showed good bending strength compared with standard concrete for all the lengths and percentages of fibre used. With an increase in the proportion of steel fibre for steel-1 in the concrete mixture, there was a significant increase in the flexural strength. It can be seen that the flexural strength of all mixture samples with different types of fibres was more than that of the control concrete. The test results show that the FRC and the control concrete generally had similar effects in terms of split tensile and bending properties. The flexural strength of the FRC increased with a higher fibre volume fraction for all types of fibre used in this study. For example, in comparison with the control specimen, the flexural strength of PFRC-1, PFRC-2, SFRC-1 and SFRC-2 increased by adding fibres about (11%, 3%, 0%), (11%, 4%, 7%), (3%, 5%, 5%) (5.5%, 6%, 7%), respectively. The results show that the highest bending force was 6.09 MPa in the concrete with fibre that contained 1.5% plastic-2 fibres. The lowest slump value was 4.70 MPa for the control mixture without fibre.

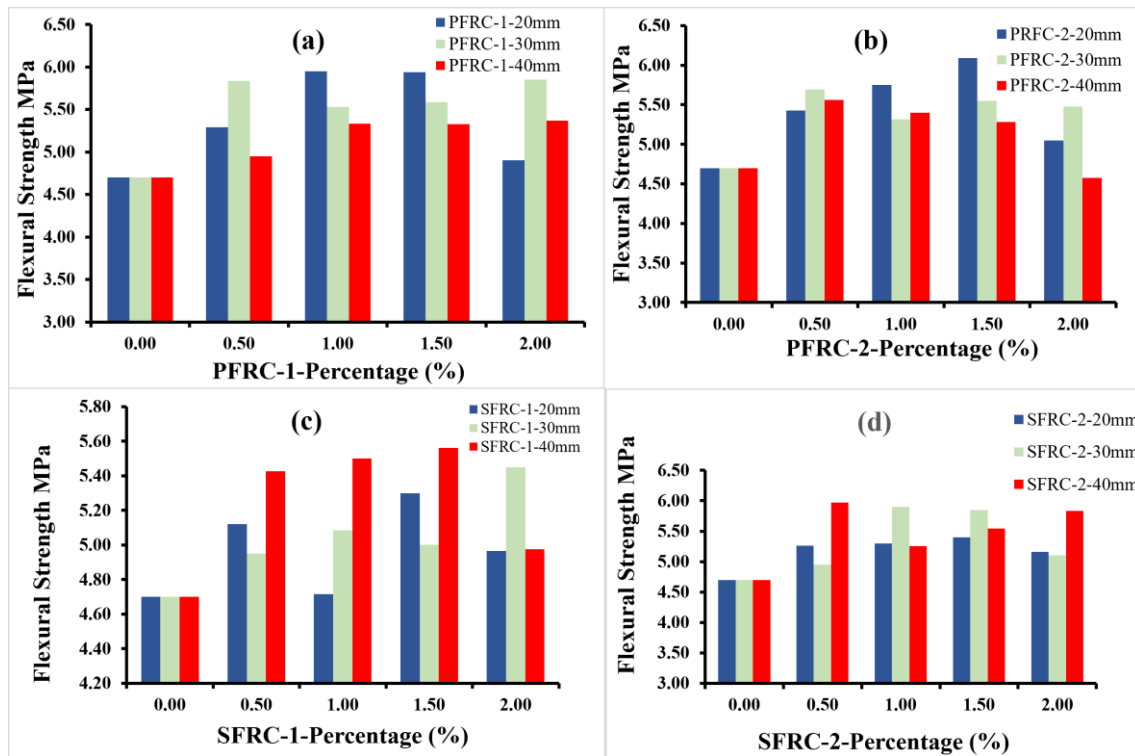


Figure 4-5 influence of steel-1 fibres on flexural strength of concrete.

The test results reveal that the FRC and the control concrete generally had similar effects on split tensile strength and bending properties. The flexural strength of the FRC increased with a rise in steel fibre volume fraction and length in both types used in this study. For example, in comparison with the control specimen, the flexural strength of the PFRC-1, PFRC-2, SFRC-1 and SFRC-2 increased by adding fibres about (13%, 14%, 18%) (15%, 26%, 27%) (0%,0%, 5%) (20 mm, 30 mm, 40 mm), respectively. The flexural strength of the FRC decreased with an increased plastic fibre volume fraction and length in both types used in this study. For example, compared with the control specimen, the flexural strength of PFRC-1 and PFRC-2 increased by adding fibres about (26%) (30%) at (20 mm). However, the flexural strength decreased when the volume at length (30 mm, 40 mm) around (24%,0%, 14%) and (21%, 18%), respectively.

4.3 Discussion

4.3.1 Workability of Fibre Reinforced Concrete

Workability is an essential factor in the approval of any mixture design. It can be used in the development of the construction industry in accordance with BS EN 12350-2 [314]. In comparing the side effects of the fresh concrete properties for all mixtures, it is possible to ensure that the addition of fibres to the concrete had an impact on the workability of the concrete. Hence, the fibre requires the addition of a superplasticizer to mixes, which leads to improved concrete workability. Recent research has investigated the workability of assessing fibre concrete production possibilities. Samples of concrete reinforced with plastic and steel fibres performed poorly. In addition, the flow of concrete decreased with an increase in fibre length and aspect ratios. The lengths of all types in this study at (40 mm) of fibres reinforced concrete mixes showed slightly less workability performance than smaller steel fibre at length (20 mm) reinforced concrete. However, the measured flow values are consistently within the range of the specified flow values. The workability of both types decreased, but the impact of steel fibre (SFRC1, SFRC2) on workability was lower than that of plastic fibre (PFRC1, PFRC2). One of the reasons for the reduced workability was thought to be the length of the fibre. The results of this test show that a 20 mm length of fibre has less influence on fresh concrete than lengths of 30 mm and 40 mm for steel (SFRC1, SFRC2) and plastic (PFRC1, PFRC2) fibre. Thus, the results show that as the amount of fibre increases, workability decreases. Several researchers have used Workability tests because they seem to be reliable and straightforward in their application. In [315], the researchers report reductions in workability with an increased fibre amount of the concrete specimen. Other studies have observed decreased fresh concrete workability when either of two kinds of SF was combined [184]. Other researchers observed that slump values were enhanced at plastic levels below 20%, with slump loss reductions of as much as 30% [117]. Workability was also found to decrease when polyethylene terephthalate (PET) was added, which was attributed to the sharpness of PET increasing the water requirements of the concrete [127]. The study found that all types of fibre decreased workability but that this issue could be avoided by adding

materials, such as a superplasticizer, or using equipment to vibrate the concrete. In the present study, the shape and ratio of the fibres had a considerable impact on concrete flow and the level of skill required by workers to produce high-quality concrete constructions. In a review of higher levels of cement, fine aggregate or fibre additions may be useful in this area, as the reinforcement of fibre additions can improve sample responses and lead to an improvement in which the shape of the fibres is reduced to focus on workability.

4.3.2 Mechanical Properties

To meet the objectives of this study, 49 FRC mixtures were created out in the laboratory, including a control concrete mixture. The tests carried out in the study were on the fresh state and mechanical properties of the concrete (compression strength, tensile strength and bending strength).

4.3.2.1 Compressive strength

The compressive strength of control concrete was higher than that of the concrete that contained fibres. The result points to the addition of too much steel and plastic fibre leading to a weak mix, which decreases compressive strength (as shown in Figures 4-2 and 4-3). The results indicate that an increase in SF can raise the maximum load capacity. The maximum load capacity was significantly impacted by the addition of fibres to the concrete. The relationship between the load and the displacement of the concrete sample was shown by adding different quantities of steel fibre and replacing the fibre with cement without transverse reinforcement.

A more quantitative examination revealed a 20% increase in maximum load capacity with an addition of 30 kg/m³ SF. Moreover, there was no significant effect on the behaviour of the compression force. SF was found to be more effective with recycled aggregates compared with natural aggregates and, therefore, could replace the mix design [103]. Li et al. note that SFRC obtained an acceptable plastic deformation, but this deformation was low compared with that of conventional concrete [316]. Other results suggest that the compressive strength of concrete using recycled SF and recycled steel cords exceeded that of SFRC

[170]. Other researchers found that the compressive strength of recycled aggregate concrete was about 72.26% of natural aggregate concrete, but, after adding silica fume, the compressive strength of concrete with recycled PET increased slightly (by 3.6-9%). The impact of steel and plastics has been studied by previous researchers. Steel fibre has increased the compressive strength, but not much and in the case of plastic fibre, no impact has been observed in mechanical properties.

The results of the tests in this study show that the FRC and the control concrete generally had similar effects in terms of compressive properties. The maximum strength of the PFRC-2 compressive samples tested also increased with the volume fraction of the fibre, about 6% compared with the control sample (1%) at 30 mm, and the strength of the concrete matrix. For example, in comparison with the reference specimen, the compressive strength of the PFRC-1 specimen increased by 6%. As concrete strength, especially compressive strength, is a fundamental characteristic related to the widespread use of this material, incorporating fibre into concrete requires a strength evaluation of the concrete-fibre composite. Incorporation can lead to several technical advantages. However, it is essential to produce a composite that is durable. Nevertheless, if the resistance of the concrete-fibre composite is significantly lower than that of the reference concrete, the realistic possibilities for it being used in various concrete applications can be minimal.

4.3.2.2 Split tensile strength.

Assessment was conducted to analyse the different types of FRC resistance relationships between tensile strength and other mechanical concrete properties. Compared with standard concrete, the addition of PFRC-1, PFRC-2, SFRC-1 and SFRC-2 fibres to concrete significantly increased the tensile strength ratio. Similar to the aforementioned results found in the literature, the split tensile strength measured in this study for 1% volume PFRC-1 was about 3.9 MPa. According to Pereira et al., the tensile strength of concrete fibres compared with the reference concrete was strongly influenced [186]. Other researchers suggested that a decrease in tensile strength with the addition of e-plastic was

caused by the replacement of the aggregate with e-plastic. However, an increase in tensile properties with a higher percentage of e-plastic waste was attributed to the increased ratio of resin, resulting in better moistening and encasement of the gaps in the materials [112]. Ameri et al. demonstrated that tensile strength increased with the addition of SF content. However, one configuration exhibited a lower w/c ratio and reduced tensile strength[95,187]. All fibre lengths tested assisted direct tension by forming and connecting multiple microcracks. The fibres maintain both sides of the cracks, and the steel and plastic fibres did not allow the crack width or macrocracks to grow. The PFRC-1 sample did not break in half due to the plastic fibre connection, keeping good integrity. There was a noticeable drop section of the side load-deformation curve for the sample with FRC. The results indicate that the mixture of plastic fibres altered the tensile fracture mode of normal concrete from the brittle fracture of the plastic fracture. After the maximum tensile fracture load was reached, the crack width continued to expand, as shown in Figures 4-6 and 4-7.

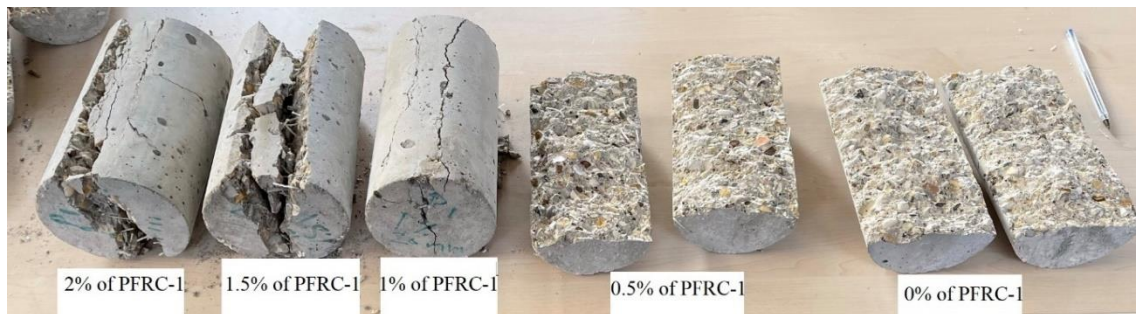


Figure 4-6 Impact of PFRC-1 (20 mm) on split tensile strength.

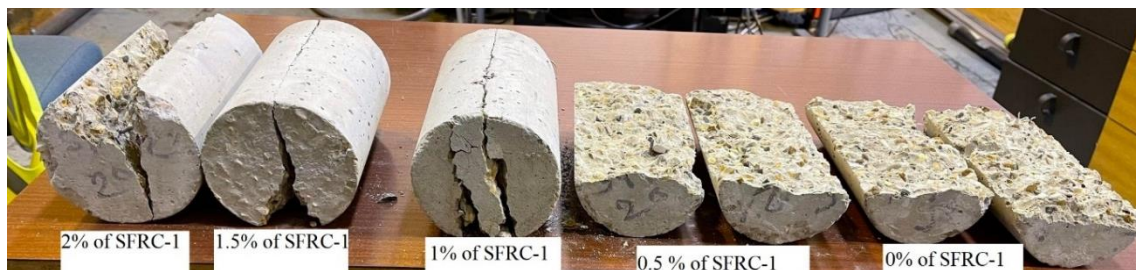


Figure 4-7 Impact of SFRC-1 (20 mm) on split tensile strength.

PFRC-1, PFRC-2, SFRC-1 and SFRC-2 helped to transfer the load into the concrete. The samples with fibres at a volume fraction of 1%, 1.5% and 2% did

not split into two parts because the PFRC-1 connected the two parts of the concrete matrix when the sample was subjected to the maximum tensile break load. This process revealed that PFRC-1 was more efficient than PFRC-2 at restraining crack-width expansion. SFRC-1 is longer and has a more significant aspect ratio than SFRC-1, SFRC-2 and PFRC-2, so its bond force with the concrete mix is also more significant. It is clear that the enhancement in tensile strength is much greater than that of compression strength. Therefore, the effect of fibre volume fraction on tensile properties also has a good impact, especially when increasing the length of the fibre. The results show increases in tensile strength.

4.3.2.3 Flexural strength

There were significant improvements in bending resistance, maximum stress deformation, toughness, and residual strength. Compared with the impact of fibre percentage on flexural strength, the impact of the resistance of the FRC mix was greater than that of the control concrete.

It should be noted here that the flexural strength of PFRC-1, PFRC-2, SFRC-1 and SFRC-2 increased sufficiently. Compared with the control specimen, the bending force was increased by additional fibre. For example, the bending restraints improved with approximately 12%, 15% and 18% of the SFRC containing an amount of 1.5% and 20 mm, 30 mm and 40 mm with different lengths of corrugated steel fibres, respectively. However, the results indicate that the addition of too much steel and plastic fibre leads to low mixing, which reduces bending. The fibres are distributed randomly in the concrete, indicating that the directions of most of the fibres vary from those of the axial load.

The addition of fibres to a concrete mix can reduce crack initiation and propagation. Fibres also provide greater flexibility in structures against crack propagation and, therefore, lengthen the catastrophic failure time and improve the mechanical properties of concrete [11]. The presence of fibres has been shown to affect the cracking resistance of concrete and improve other properties [44]. The addition of SF has been shown to improve mechanical properties, including crack resistance and toughness [44]. The addition of SF also improved

mechanical properties, including crack resistance and toughness, and Sengul showed that SF was more effective in increasing crack-growth resistance due to its geometric and material properties [317]. This study improved bending strength of PFRC and SFRC was significantly greater than that of standard concrete.

Furthermore, with the impact of fibre volume fraction on flexural properties, fibre length also had an effect, particularly with increasing length; the results showed increases in bending force. The SF of both types improved the bending strength and reduced cracking when increasing the length of the fibre. However, the flexural strength was reduced when the length of the plastic fibres of both types was increased. Figures 4-8 and 4-9 explains the significant impact of fibre length on cracking propagation.

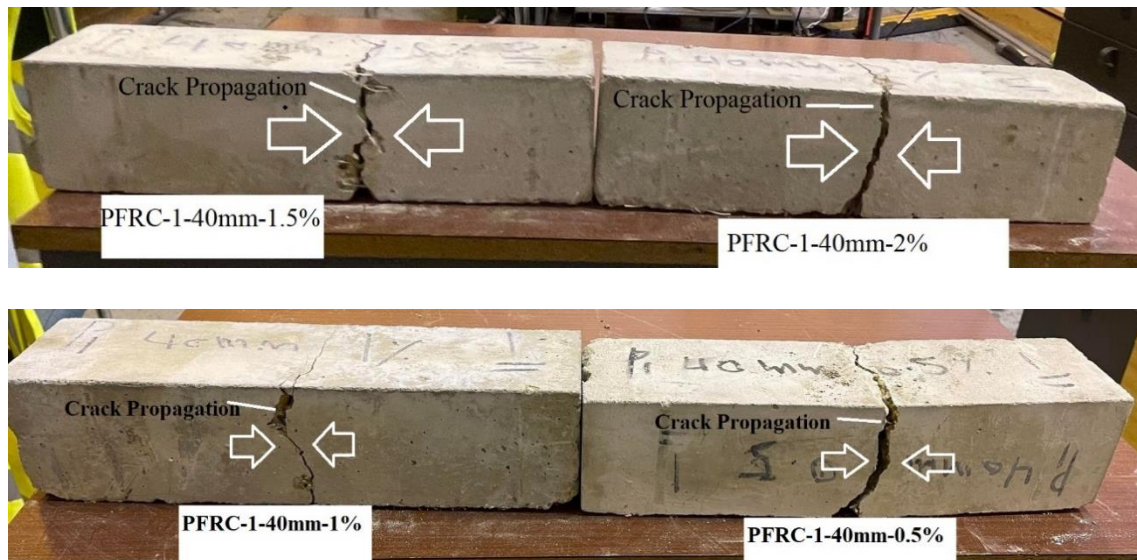


Figure 4-8 Impact of PFRC-1 (40 mm) on flexural strength.

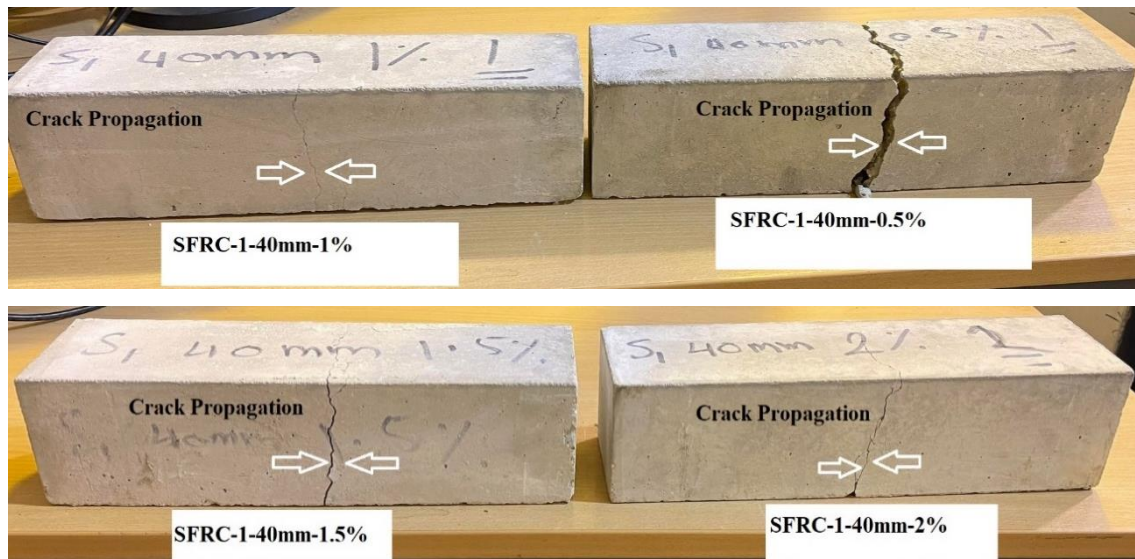


Figure 4-9 Impact of SFRC-1 (40 mm) on flexural strength.

This result was expected because the code demonstrates that the bending resistance directly relates to the tensile strength properties of the concrete. Since the tensile failure increased with the increase in the length of the in steel and plastic fibres, it was expected that the bending force would also increase. However, the reduced bending resistance can be attributed to the length and amount of the plastic fibres.

4.4 Parametric Analyses for the Optimization of FRC

This optimization study demonstrates a correlation between the mechanical and fresh-state properties of concrete using fibre parameters, including the length, type, and amount of fibres, to obtain the optimal value of fibres. The input parameters included the way in which the volume, type and length of fibres affect the reinforced concrete mix. As mentioned in the results section, the length and type of the fibres have a significant impact on the optimal value. An increase in plastic fibre length from 20 mm to 40 mm had a negative impact, decreasing the mechanical properties. However, increases in the length of SF increased the strength of the concrete in terms of bending and tensile strength. In addition, increases in the amount of both types reduced the fresh-state and mechanical properties. Researchers have reported reductions in workability with an increase in fibre amount and length of the concrete specimen. Different studies observed

decreased fresh concrete workability when either of two kinds of SF was combined [13-32]. Researchers have also suggested that a decrease in tensile, compressive and flexural strengths with the addition of e-plastic was caused by the replacement of the aggregate with e-plastic [40].

A significant influence of parameter on type is cost because the price of plastic according to the Fibre Concrete Solutions Limited company is double that of the steel fibre price. Concrete is considered a cost-effective long-term solution for concrete design. Prices of steel and plastic fibres will vary considerably depending on their physical properties and whether they are used for structural advantages in concrete or non-structural advantages in plastic (microfibre). Thus far, the evidence supports the idea that the fibre length and percentage are influenced by ease of mixing of the fibre, especially in the workability of concrete. Statistical experimental design approaches are stringent techniques for achieving the chosen properties and determining an optimized mix for a given set of limitations [318]. They are widely utilized in industry to optimize products and procedures and have been used in investigations into enhancing high-performance concrete. The concretes with 1% of steel fibre was optimal value, after combining all input and output parameters by using the equations we explained. the mechanical results and fresh concrete tests are considered output parameters including compressive, split tensile, flexural, and workability (44.47 MPa, 3.64 MPa, 5.30 MPa, and 6.5cm) as shown in Figure 4-10. For the input parameters, we considered the steel fibres cheaper than plastic according to price information had from the LTD suppliers. The other two input parameters will combine as explained at the beginning of the optimization study. after done the calculation the highest number means highly optimized concrete was 42.44.

These results should be considered when considering how to optimize any FRC because this method considers the properties of all the parameters that have an impact on mixed concrete, such as the influence of workability, durability, strength, and the crack resistance of the concrete (type, cost and amount of fibres).

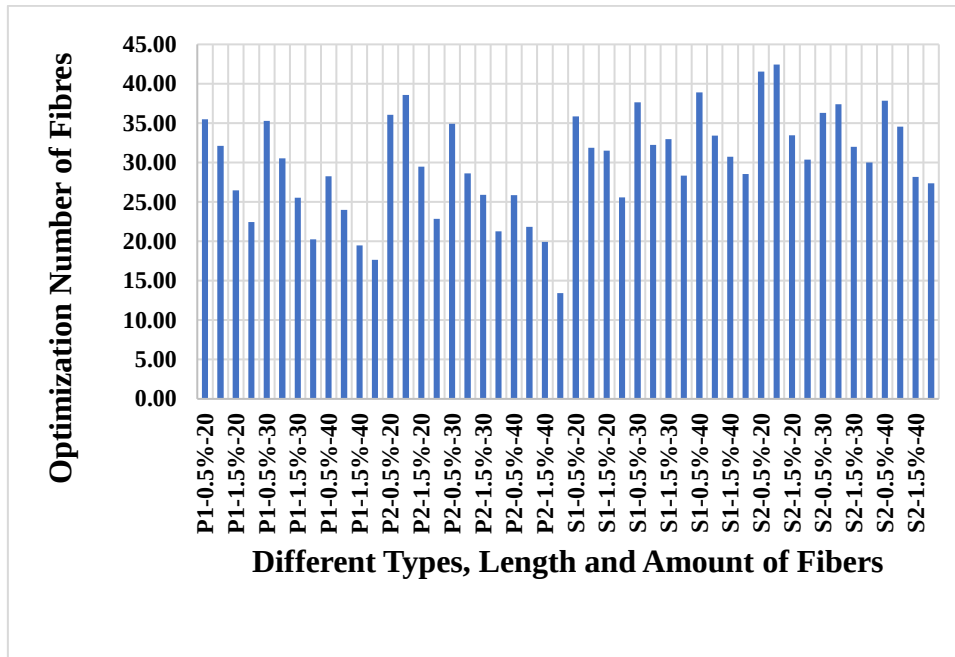


Figure 4-10 Parametric analyses for the optimization of FRC.

4.5 Conclusions

This chapter presented the results of extensive experimental research aimed at optimizing the mechanical properties of conventional concrete and developed an optimization method based on parametric analysis for the optimization of FRC to find an optimal fibre value for reinforced concrete. The findings of this research project offer the following conclusions.

- It is evident from the results that workability is reduced when the amount of fibre increases. The length of the fibre is considered one of the reasons for the reduced workability.
- The enhancement in compressive strength is the same as the compression strength of normal concrete.
- It is also clear that the enhancement of tensile strength is much greater than that for compression strength. The fibres maintain both sides of the cracks, and steel and plastic fibres did not allow the crack width or macrocracks to grow. Therefore, the effect of fibre volume fraction on tensile properties also has a good impact, especially when the length of the fibre is increased. The results showed increases in tensile strength.

- The improved bending strength of both types of PFRC and SFRC was significantly greater than that of standard concrete. Furthermore, with the impact of the fibre volume fraction on flexural properties, the fibre length also had an effect, particularly when this was increased; the results showed increases in bending force and decreased initial crack.
- The optimum value was found to be SFRC-2-20mm-1%, which had compression, tensile failure, bending strength, and workability values of 44.7, 3.64, 5.3, and 6.5 cm, respectively.

The optimization method presented in this chapter provides new critical insight into the relationship between output and input parameters. These results should be considered when considering optimization for any FRC because this method considers the properties of all the parameters that have an impact on mixed concrete, such as workability, durability, strength, and the crack resistances of concrete (in respect of type, cost, and amount of fibres).

5 Modelling the Relationship between Fibre Features with Optimum Mechanical Properties

5.1 Introduction

Most of the earlier research referred to in Chapter 2 concludes its analysis without considering the collective influence of key fibre parameters, such as the shape, type, length, and percentage. There is still a need for a model that can consider these key parameters as an input and provide the properties of reinforced concrete as an output, and to facilitate the user in analysing the optimal fibre addition as per the construction requirements. Thus, this chapter proposes the Khan Khalel model, which can be used to predict the desirable compressive and flexural strengths for any given values of key fibre parameters. Statistical tools are used to develop and validate the model with numerical results. The proposed model is easy to use but predicts compressive and flexural strengths with errors under 6% and 15%, respectively. This error primarily represents the assumption made for the input of fibre material during model development.

This chapter is structured as follows. The results, together with a discussion of the experimental tests of the influence of fibre parameters on compressive strength and of fibre parameters on flexural strength, are presented in Section 5.2. A numerical model is outlined in Section 5.3, which includes numerical analyses of flexural strength (5.3.1) and compressive strength (5.3.2). Section 5.4 presents a comparison between the numerical model and the experimental results, including the compressive (5.4.1) and flexural (5.4.2) strengths. The development of the Khan Khalel model is presented in Section 5.5.

5.2 Results and Discussion of the Experimental Tests

5.2.1 Influence of Fibre Parameters on Compressive Strength

As shown in Figure 5-1, the compressive strength of the control concrete was greater than that of the fibre-containing concrete. The results indicate that steel and plastic fibres were added, resulting in a weak composite with low compressive strength. However, flexural strength properties were increased. The results indicate that the compressive strength of concrete increased slightly for two lengths of PFRC2 fibre in the concrete mix (20 mm and 30 mm). However, as indicated in Figure 5-4 there were

no compressive impacts over a length of 40 mm. The compressive strength dropped slightly when the percentage of SFRC1 was increased by adding fibres of 20 mm, 30 mm, and 40 mm to the concrete mix. In contrast, this slight compression was higher than the concrete mixture's planned compression level of 30 MPa. The compressive strength increases as the proportion of SFRC2 at 40 mm in the concrete mix increases. However, at lengths of 20 mm and 30 mm, no compressive influence was seen. In past, researchers tested the compressive strength of the FRC and discovered that the fibres enhanced stress resistance. Similarly, other researchers [319–322] substituted coarse and fine particles with fibres to improve the mechanical properties of concrete. Other research suggested that the use of steel and e-plastic reduces compressive strength because the aggregate is replaced by steel and plastic fibres [172,323–327].

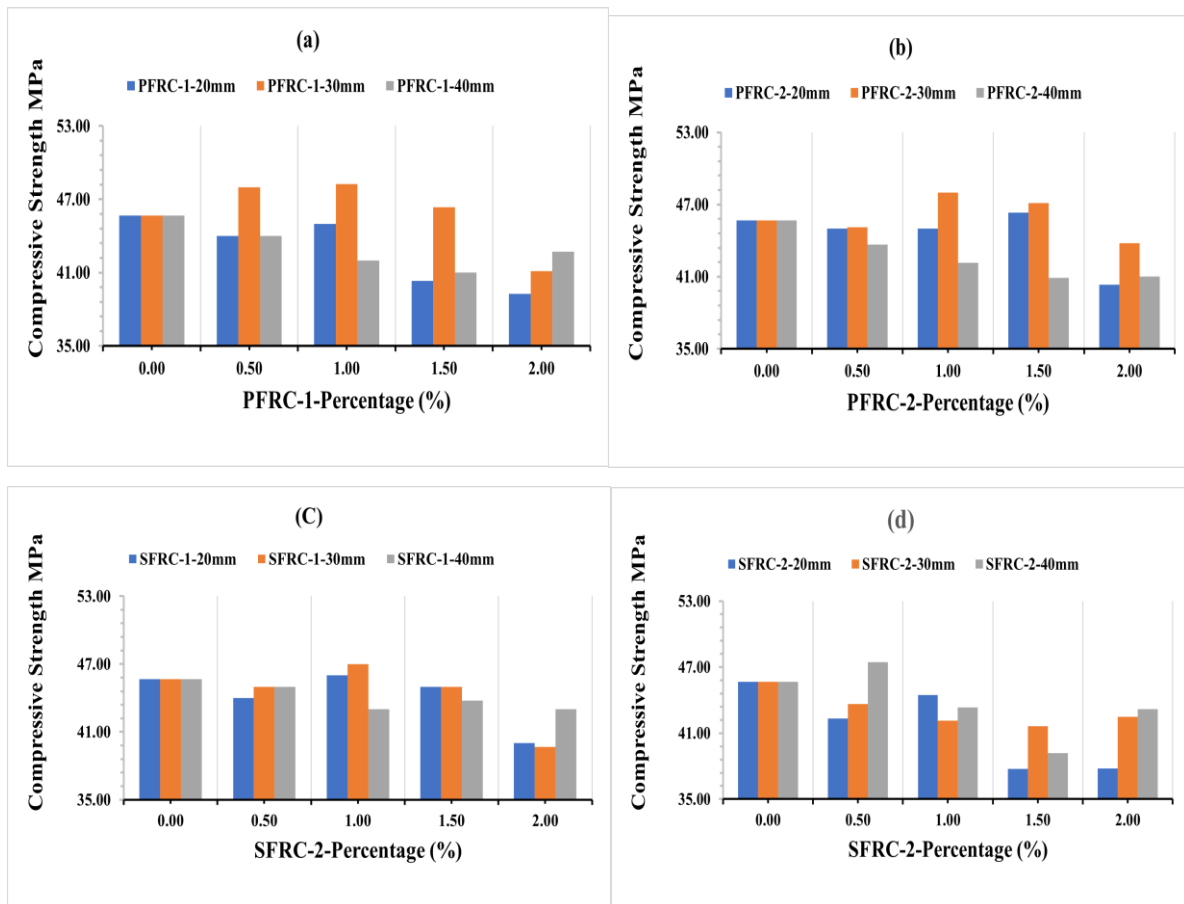


Figure 5-1 Impact of different types of fibres on concrete compressive strength.

Overall, the compressive strength of FRC decreased when compared to the compressive strength of standard concrete. Moreover, fibre length has a negative effect on the compressive qualities when considering how the fibre content influences them, significantly when the length is increased, as evidenced by the results, which showed a drop in compressive strength.

5.2.2 Influence of Fibre Parameters on Flexural Strength

A flexural load was applied to 98 prisms of FRC samples with various lengths, forms, and fibre volume percentages. Figure 5-2 illustrates the influence of fibre type, shape, and percentage on flexural strength after 28 days for different fibre types. The flexural strength increased somewhat when the percentage of plastic-1 fibre in the concrete mix with lengths of 20 mm, 30 mm, and 40 mm increased. Compared to conventional concrete, Plastic-2 FRC showed excellent ductility for all used fibre lengths and percentages. The flexural strength increased significantly with the steel fibre percentage for steel-1 in the concrete mixture. All mixture samples with various fibres have higher flexural strength than the control concrete. Furthermore, when the amount of fibre increases, so does the transverse deformation of the sample. The stress induced by the external load is effectively communicated between the steel fibre and concrete matrix, allowing the steel and plastic fibres to completely utilize their flexural strength and compensate for the FRC matrix's lower tensile capacity. Steel fibre can bridge large cracks because the interface between steel, plastic fibre, and concrete has a specific bond strength. Therefore, the specimen will not have a severe fracture because the cracks are constantly growing. However, the number of cracks will increase significantly during this procedure, as will the crack width. As a result, the crack expands dramatically, causing the transverse deformation of the specimen to increase. Previous research findings have validated the technique of enhancing flexural strength by increasing polypropylene fibre content, as it demonstrated improved flexural performance in both equivalent durability and flexural strength with an increase in the percentage of SF used [194,328]. The increase in flexural strength is much more significant than the increase in compressive strength. As a result, the impact of fibre content on flexural characteristics is substantial when the length of the fibre is increased as shown in Figure 5-2. The more significant the reduction in cement usage, the greater the reduction in eCO₂ and the further the realization of sustainable growth in the construction industry.

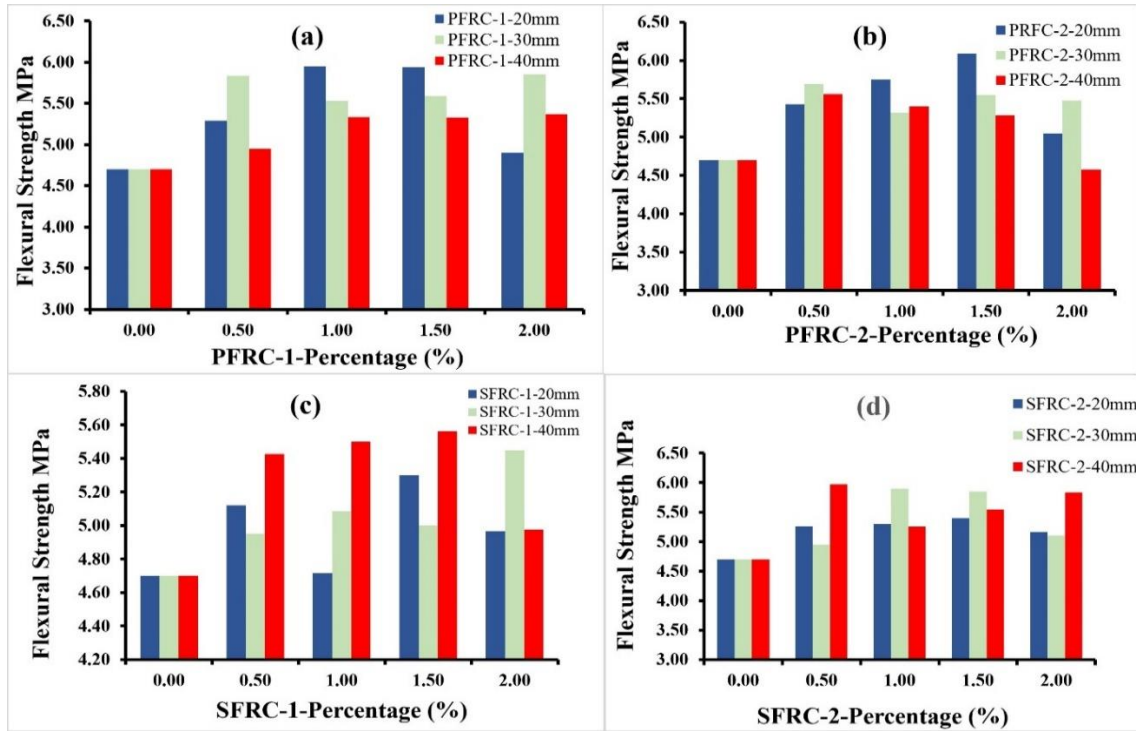


Figure 5-2 Impact of different types of fibres on concrete flexural strength.

In general, FRC's flexural strength increases compared to standard concrete's flexural strength. Moreover, fibre length negatively influences the flexural strength when considering how the fibre content affects them, significantly when the length is increased, as evidenced by the results, which showed a decrease in flexural.

5.3 Numerical Model

5.3.1 Numerical Analysis of Flexural Strength

In numerical model, the samples were notched in the centre and failed in their flexural capacity, with a substantial crack down the length of the beam. The typical failure mechanisms of the 48 beams are shown in Figure 5-3 and Figure 5-4. Although the beam geometry, boundary, and loading conditions were all symmetric, the cracks in several of the beams were slightly convoluted and strayed from the centre beamlines. This is due to the random distribution and orientation of the steel and plastic fibres [329,330], which increases the crack-tip stress fields and the extremely heterogeneous local tensile strength and fracture toughness, as in ordinary concrete where aggregates behave similarly to steel fibres [331]. This cannot be accurately represented by the homogeneous models used in this investigation and can only be simulated by models that directly or indirectly consider random heterogeneity [332–334]. According to the CDPM, two failure processes for flexural strength were

observed in this study. When a vertical crack propagates from the corners of the opening to the applied load and support, the first mode is a diagonal splitting failure. When a diagonal fracture forms in the shear span, it causes high strains inside the compression chord of the apertures next to the site of the loads. Figure 5-3 shows how the damage to concrete plasticity in the simulation creates failures consistent with actual observations. There were noticeable differences between the numerical and experimental data for the mechanical properties in previous research, including flexural and cracking tensile strength [335,335,336]. Figure 5-5 shows the max load in the middle and max displacement of SFRC-2 beams obtained from the numerical model, and that load was used to calculate the flexural strength according to BS EN 12390-6 (2009). This is comparable to the experimental results obtained from the specimens in this study, as shown in table 3-2 with different lengths, shapes, and percentages of fibre. The contour plots in Figures 5-3 and 5-4 show the damage levels in various colours, ranging from the most severe to the least, in red, yellow, green, and blue. The images show that the crack propagation of beam distribution is equal along the middle axis, similar to the beam in the experimental observation. The estimation of the flexural strength for all the beams is also acceptable in terms of agreement with the experimental results.

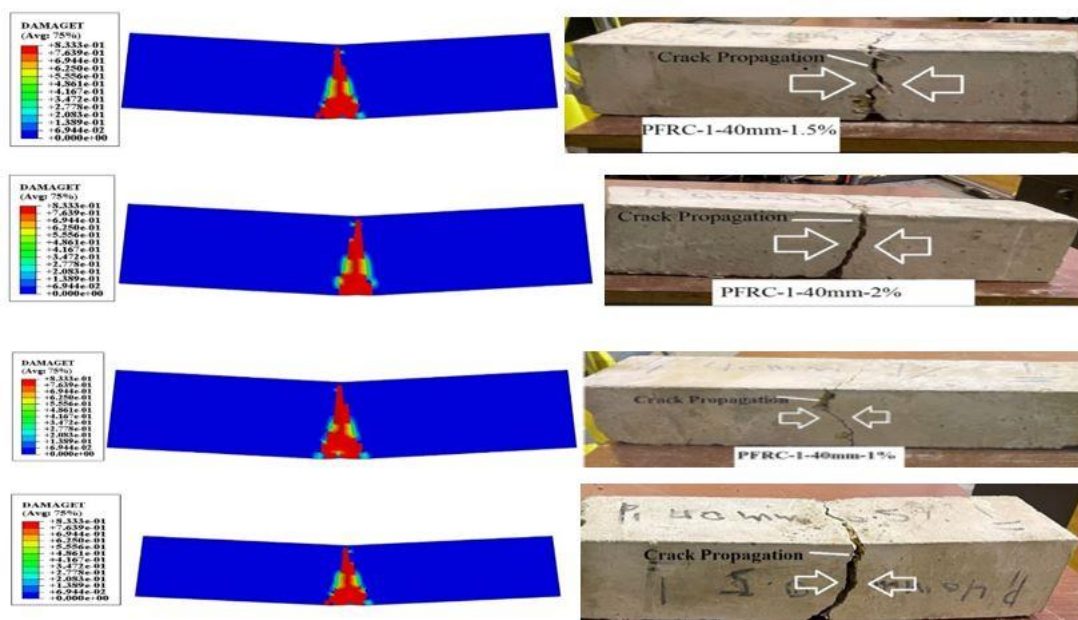


Figure 5-3 Comparison of the numerical and experimental results of PFRC-1 (40 mm) for flexural strength.

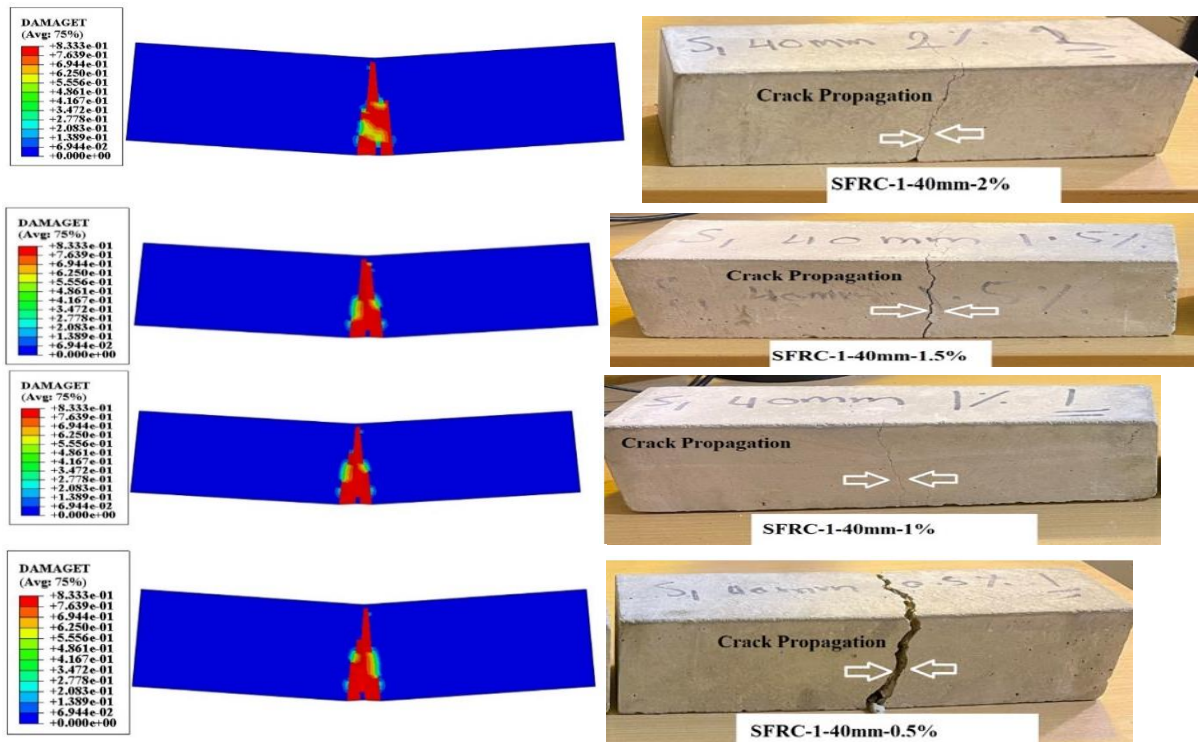


Figure 5-4 Comparison of the numerical and experimental results of SFRC-1 (40 mm) for flexural strength.

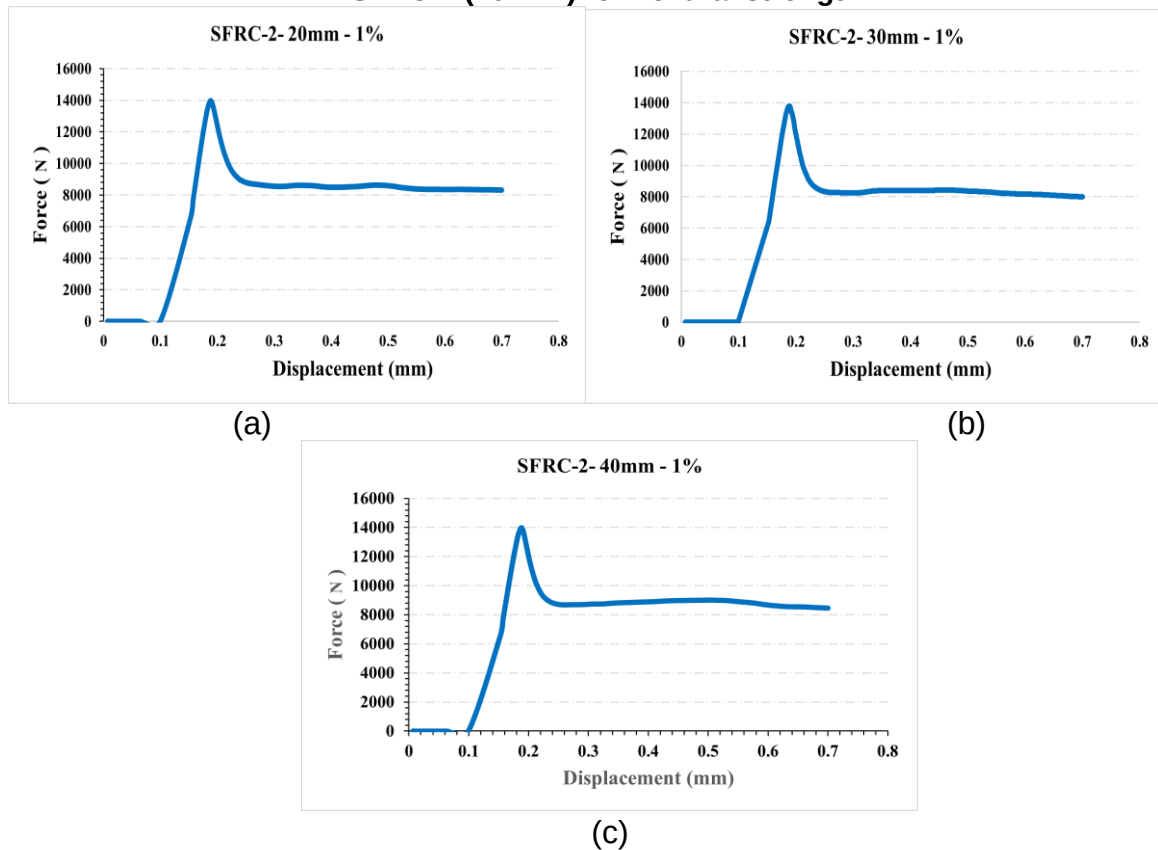


Figure 5-5 Max load in the middle of beams and max displacement obtained from the numerical model.

5.3.2 Numerical Analysis of Compressive Strength

The CDPM output can provide information on the damage distribution and characteristics of the concrete cube at various stages through numerical analysis. The concordance between the estimates from the suggested formula and the findings of the numerical analysis demonstrates compressive strength [337,338]. Figure 5-7 shows the max load applied on the cube of SFRC-1 at 1% and max displacement obtained from the numerical model, and that load was used to calculate the compressive strength according to BS EN 12390-4 (2000). This is comparable with the experimental results obtained from the specimens, as shown in Figure 5-6 (b). Figure 5-6 (c)–(e) shows the damage contours of the three views (YX, ZX, and YZ) in Figure 5-6 (a). The contour plots show damage levels in various colours, ranging from the most severe to the least, in red, yellow, green, and blue. The images show that the damage distribution is equal along the middle axis, like the experimental observation. Furthermore, by observing the damage shapes derived by CDP and testing, it is discovered that the top and bottom surfaces of the concrete cubes stay relatively intact. Figure 5-6 (c) and 5-6 (d) shows that the damage modes at the YX and ZX portions of the specimen are X-shaped (d). The concrete mixture peeled off on four edges in all three concrete cube tests, and the samples were in a dumbbell shape at the end of the test. As a result, the numerically simulated damage contours of the sample correlate well with the experimental observations. The CDPM can be used in the compressive strength check and damage evaluation.

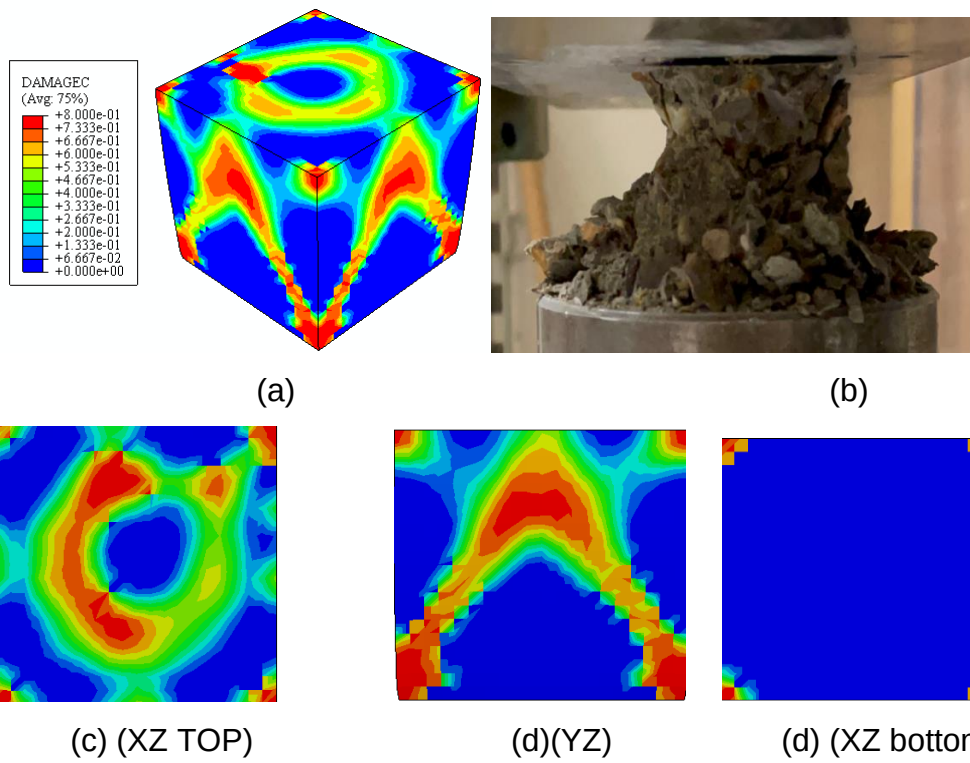


Figure 5-6 Comparison of the numerical and experimental results of the compressive strength behaviour of FRC.

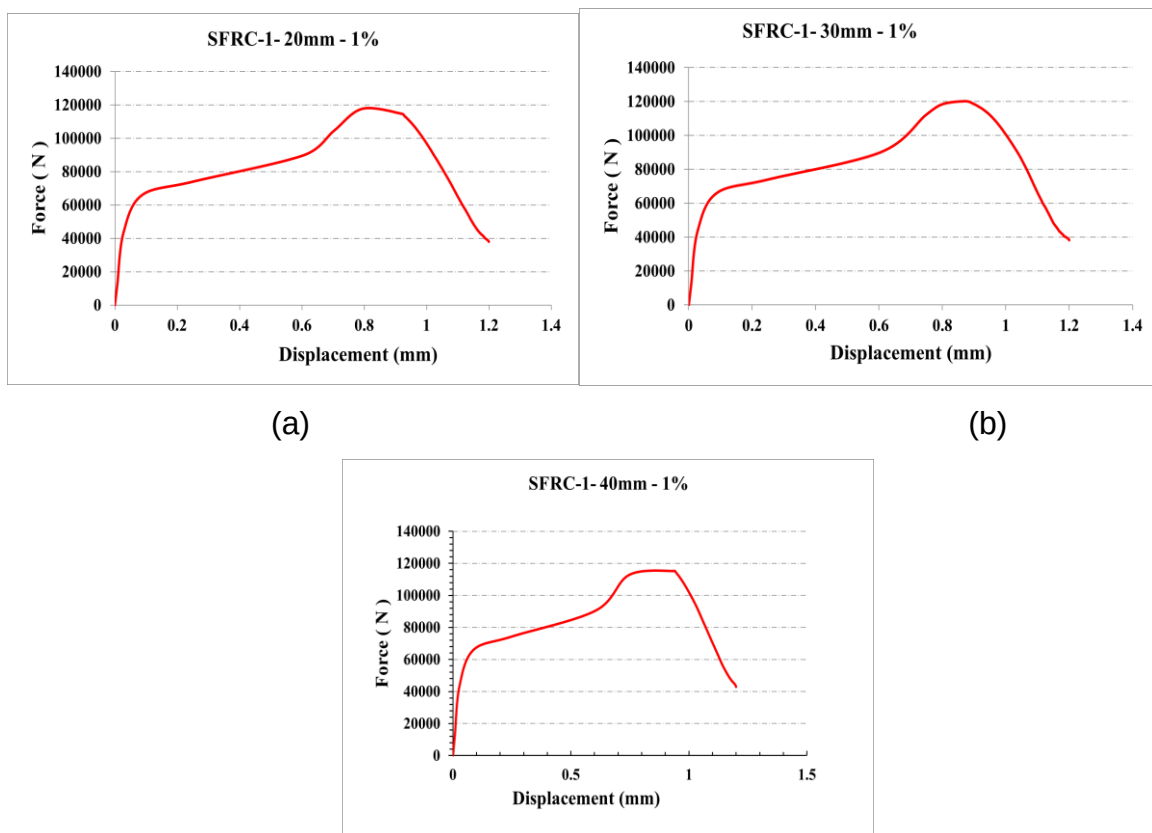


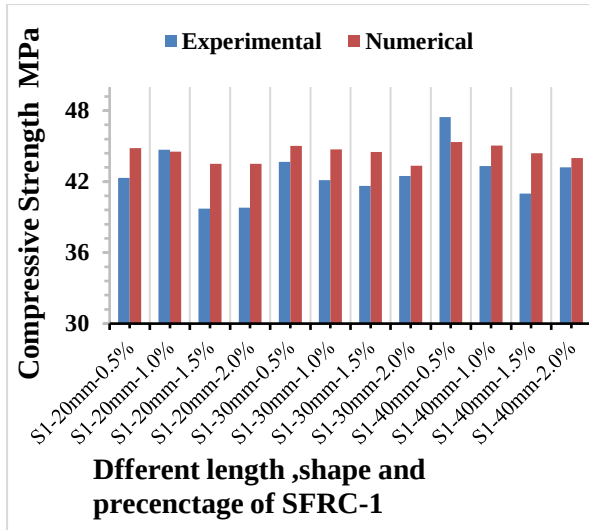
Figure 5-7 Max load applied on the cube and max displacement.

5.4 Comparison of the Numerical Model and the Experimental Results

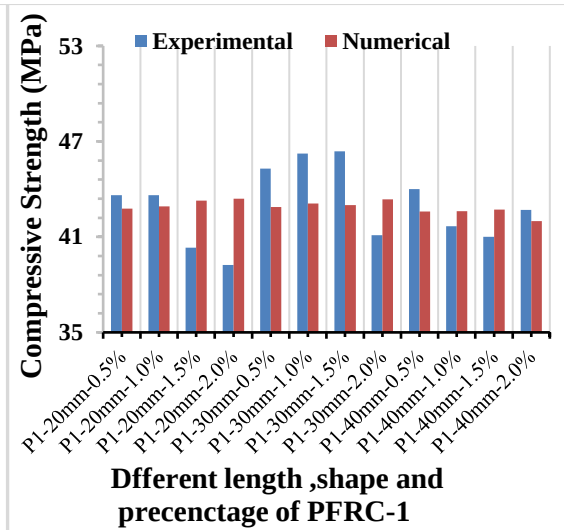
5.4.1 Compressive Strength

Compressive strength is one of concrete's most important mechanical qualities when designing a structure. The figure 5-8 shown the comparison of steel and plastic fibre reinforced concrete influence on compressive strength between experimental results and numerical simulations. The relationship between experimental data and those produced using CDP models is investigated in this section (as shown in Figure 5-9). The compressive strength of the samples ranged from 39.17 to 48.4 MPa, as indicated in Table 5-1. According to Figure 5-9, the compressive strength agrees well with the CDP model outcomes. The CPD model in this study might be an effective tool to validate the compressive strength of FRC, rather than conducting laboratory experiments based on material properties such as mechanical properties, length, and fibre percentage of fibre, concrete damage plasticity (CDP) behaviour. The CDP model has the highest accuracy in forecasting compressive strength, with a determination coefficient (R^2) of 0.9965 as shown in Figure 5-9. According to the MSE-evaluated tool results, only four of the numerical values in the CDP model showed an error (27.4%, 17.39%, 14.69%, 13.69%) between all experimental concrete strength output values (48 experimental findings).

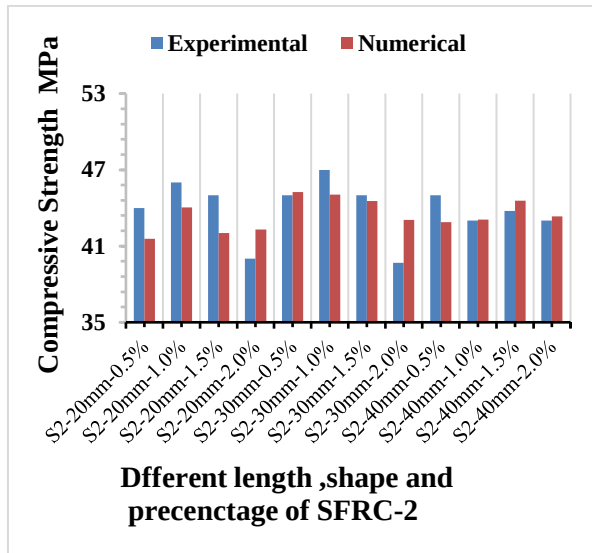
As demonstrated in this study, the CPD model can predict the optimal fibre with acceptable accuracy to obtain a compressive strength adequate for usage in a structure. This may stimulate the use of the concrete damage plasticity model in forecasting the compressive properties of concrete generated by different fibre materials in the future. To assess the accuracy of the numerical model in this study, the compressive strength of SFRC had the lowest and most significant errors, and the MAPE was between 0.18% and 12.98%; Figure 5-10 shows the MAPE results for the experimental and numerical models. Table 5-1 shows the evaluations used to analyse the results output of compressive strength.



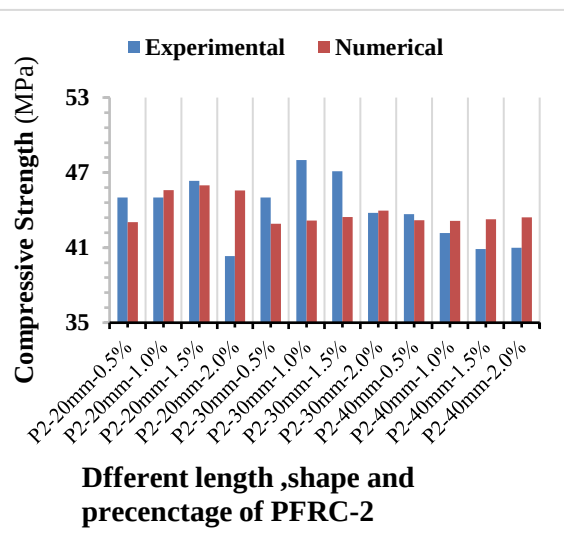
(a)



(b)



(c)



(d)

Figure 5-8 Comparison of steel and plastic fibre reinforced concrete influence on compressive strength between experimental results and numerical simulations.

Table 5-1 Compressive strength of fibre reinforced concrete.

Mixes of concrete	Elastic modulus of fibre types (MPa)	Tensile strength of different type shape (MPa)	Fibres Length (mm)	Percentage of fibre (%)	Compressive strength Experimental (MPa)	Compressive strength Numerical (MPa)	(MSE) Numerical and Experimental	(MAPE) Numerical and Experimental
SFRC-1	200000	800.00	20.00	0.50	42.33	44.84	1.44	5.92
SFRC-1	200000	800.00	20.00	1.00	44.7	44.53	4.85	0.14
SFRC-1	200000	800.00	20.00	1.50	39.73	43.50	6.19	9.48
SFRC-1	200000	800.00	20.00	2.00	39.80	43.50	14.45	9.30
SFRC-1	200000	800.00	30.00	0.50	43.67	45.02	1.80	3.10
SFRC-1	200000	800.00	30.00	1.00	42.13	44.73	5.60	6.16
SFRC-1	200000	800.00	30.00	1.50	41.63	44.50	11.90	6.89
SFRC-1	200000	800.00	30.00	2.00	42.47	43.36	13.13	2.10
SFRC-1	200000	800.00	40.00	0.50	47.47	45.34	2.64	4.48
SFRC-1	200000	800.00	40.00	1.00	43.33	45.04	6.96	3.94
SFRC-1	200000	800.00	40.00	1.50	41.00	44.40	10.97	8.29
SFRC-1	200000	800.00	40.00	2.00	43.20	44.01	17.95	1.88
PFRC-1	7000	465.00	20.00	0.50	43.63	42.77	0.78	1.98
PFRC-1	7000	465.00	20.00	1.00	43.63	42.91	0.33	1.66
PFRC-1	7000	465.00	20.00	1.50	40.33	43.29	5.13	7.32

PFRC-1	7000	465.00	20.00	2.00	39.24	43.41	13.71	10.63
PFRC-1	7000	465.00	30.00	0.50	45.30	42.87	0.67	5.36
PFRC-1	7000	465.00	30.00	1.00	46.23	43.09	0.51	6.79
PFRC-1	7000	465.00	30.00	1.50	46.37	43.00	3.77	7.26
PFRC-1	7000	465.00	30.00	2.00	41.10	43.37	13.14	5.52
PFRC-1	7000	465.00	40.00	0.50	44.00	42.60	1.27	3.18
PFRC-1	7000	465.00	40.00	1.00	41.67	42.62	0.04	2.29
PFRC-1	7000	465.00	40.00	1.50	41.00	42.71	2.60	4.17
PFRC-1	7000	465.00	40.00	2.00	42.70	42.00	4.92	1.64
PFRC-2	7000	552.00	20.00	0.50	45.00	43.04	0.37	4.35
PFRC-2	7000	552.00	20.00	1.00	45.00	45.60	10.62	1.33
PFRC-2	7000	552.00	20.00	1.50	46.33	45.98	24.52	0.77
PFRC-2	7000	552.00	20.00	2.00	40.33	45.57	34.30	12.98
PFRC-2	7000	552.00	30.00	0.50	45.01	42.90	0.62	4.66
PFRC-2	7000	552.00	30.00	1.00	48.00	43.17	0.63	2.99
PFRC-2	7000	552.00	30.00	1.50	47.10	43.45	5.69	1.48
PFRC-2	7000	552.00	30.00	2.00	43.77	43.95	17.63	0.41
PFRC-2	7000	552.00	40.00	0.50	43.67	43.20	0.28	1.06
PFRC-2	7000	552.00	40.00	1.00	42.17	43.15	0.54	2.33
PFRC-2	7000	552.00	40.00	1.50	40.90	43.28	4.73	5.81
PFRC-2	7000	552.00	40.00	2.00	41.00	43.42	13.18	5.90
SFRC-2	200000	1150.00	20.00	0.50	44.00	41.58	4.26	5.49

SFRC-2	200000	1150.00	20.00	1.00	46.00	44.04	2.92	4.26
SFRC-2	200000	1150.00	20.00	1.50	45.00	42.03	1.02	6.61
SFRC-2	200000	1150.00	20.00	2.00	40.00	42.30	6.74	5.75
SFRC-2	200000	1150.00	30.00	0.50	45.00	45.26	2.50	0.59
SFRC-2	200000	1150.00	30.00	1.00	47.00	45.04	7.13	4.17
SFRC-2	200000	1150.00	30.00	1.50	45.00	44.54	12.18	1.01
SFRC-2	200000	1150.00	30.00	2.00	39.67	43.05	10.93	8.52
SFRC-2	200000	1150.00	40.00	0.50	45.00	42.89	0.69	4.69
SFRC-2	200000	1150.00	40.00	1.00	43.00	43.08	0.45	0.18
SFRC-2	200000	1150.00	40.00	1.50	43.77	44.58	12.18	1.86
SFRC-2	200000	1150.00	40.00	2.00	43.00	43.33	12.59	0.76
Average						43.00	6.90	4.84

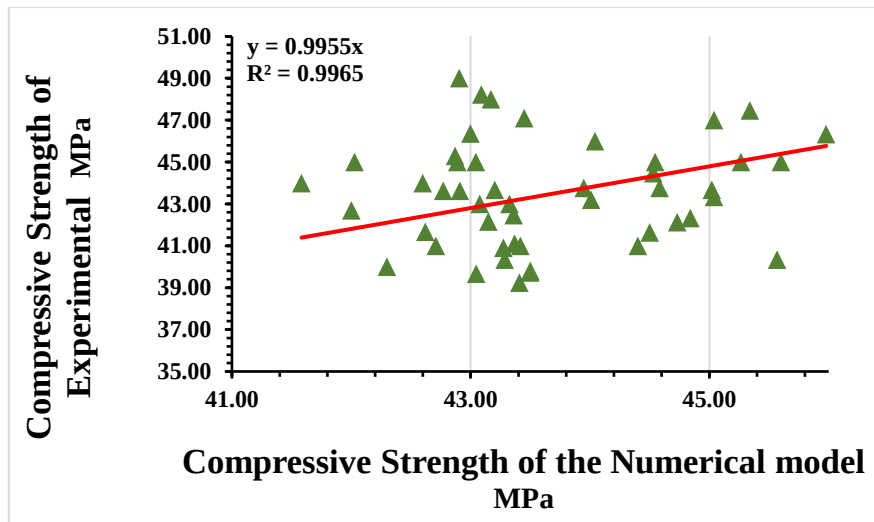


Figure 5-9 Relationship between compressive strength results for the experiment.

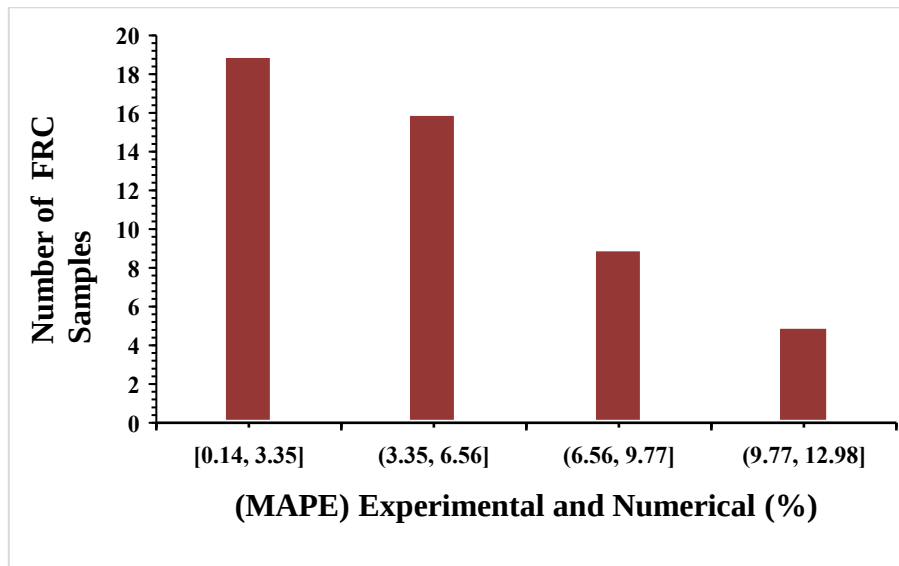


Figure 5-10 Mean absolute percentage error (MAPE) of compressive strength results.

5.4.2 Flexural Strength

As shown in Table 5-2, the experimentally determined mean values for flexural strength fall agree with the value of flexural strength that obtained by the numerical models. Figure 5-11 Comparison of steel and plastic fibre reinforced concrete influence on compressive strength between experimental results and numerical simulations.

With correlation coefficients (R^2) of 0.9972, the match between the numerical data and experimental outcomes is significantly high as shown in Figure 5-12. This enables the prediction of the flexural strength of FRC using the Abaqus software's concrete damage plasticity

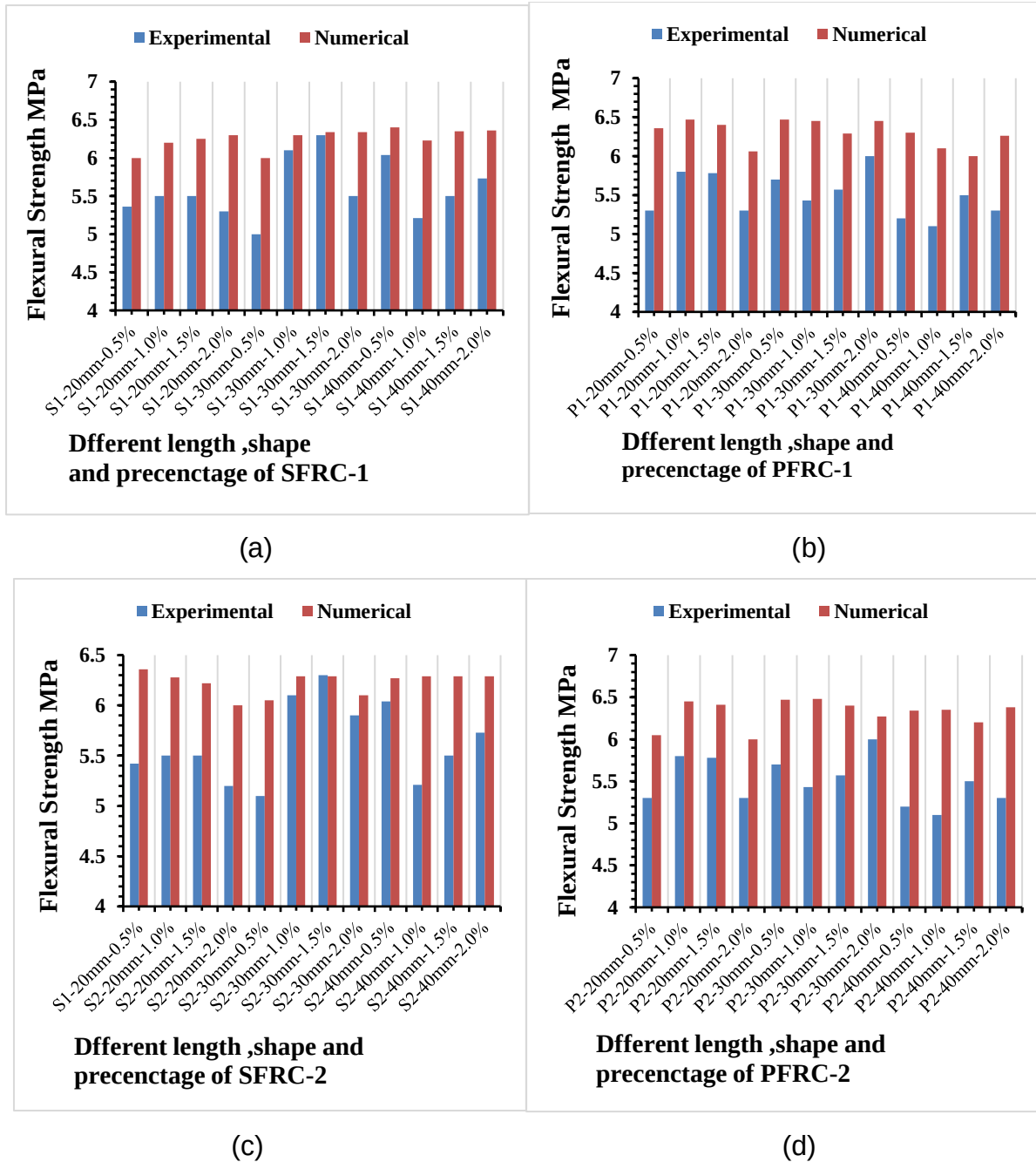


Figure 5-11 Comparison of steel and plastic fibre reinforced concrete influence on compressive strength between experimental results and numerical simulations.

According to the MAPE evaluated tool results, only four of the numerical values in the CDP model showed an error (15.1%,15.06,14.88%14.58%) between all experimental concrete flexural strength output values (48 experimental findings). As demonstrated in this study, the CPD model can predict the optimal fibre with acceptable accuracy to obtain a flexural strength adequate for using in a structure. This may stimulate the use of the concrete damage plasticity model in forecasting the flexural strength properties of concrete generated by different fibre materials in the future. To assess the accuracy

of the Numerical model in this study, the flexural strength of SFRC had the lowest and most significant errors, and the MSE was between 0.121% and 0.926 %. Figure 5-13 shows the MAPE results for the experimental and numerical models. Table 5-1 shows the evaluations used to analyse the results output of flexural strength.

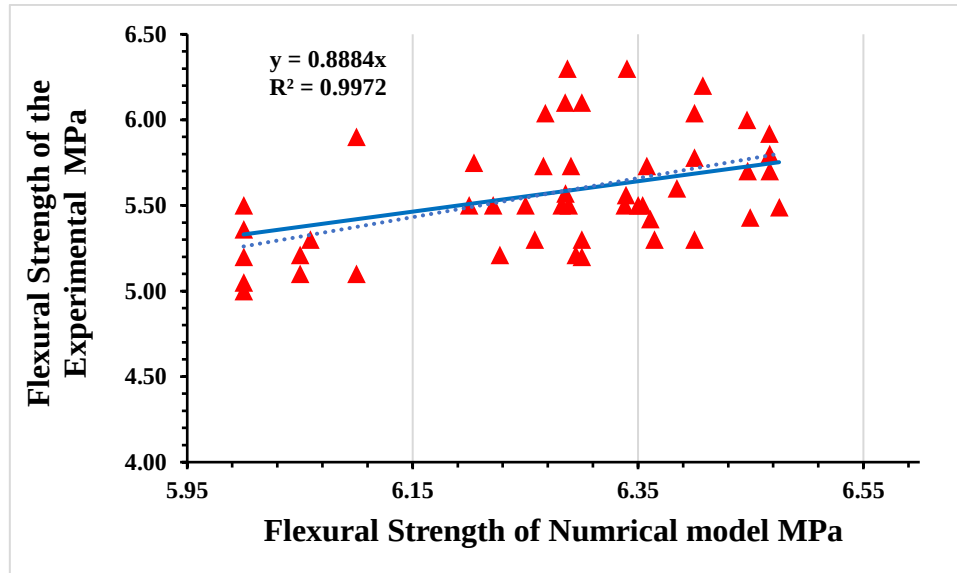


Figure 5-12 Relationship between flexural strength results for the experimental and numerical models.

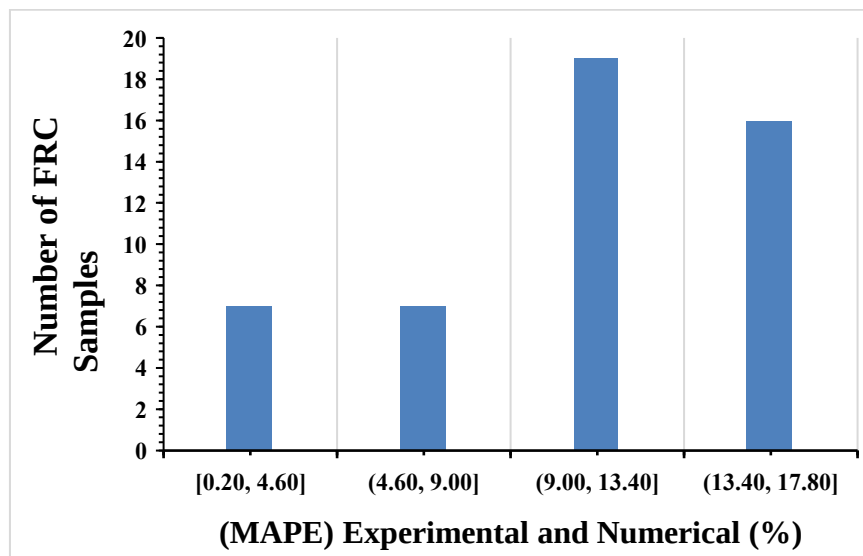


Figure 5-13 Mean absolute percentage error (MAPE) of flexural strength.

Table 5-2 Compressive strength of fibre reinforced concrete.

Mixes of FRC	Elastic modulus of fibre types (MPa)	Tensile strength of different type shape (MPa)	Fibre Length (mm)	Percentage of fibre (%)	Flexural Strength Experimental (MPa)	Flexural Strength Numerical (MPa)	(MSE) Experimental and Numerical	(MAPE) Experimental and Numerical (%)
SFRC-1	200000	800	20	0.5	5.36	6.00	0.410	10.67
SFRC-1	200000	800	20	1.0	5.50	6.20	0.490	11.29
SFRC-1	200000	800	20	1.5	5.50	6.25	0.563	12.00
SFRC-1	200000	800	20	2.0	5.30	6.30	1.000	15.87
SFRC-1	200000	800	30	0.5	5.00	6.00	1.000	16.67
SFRC-1	200000	800	30	1.0	6.10	6.30	0.040	3.17
SFRC-1	200000	800	30	1.5	6.30	6.34	0.002	0.63
SFRC-1	200000	800	30	2.0	5.50	6.34	0.703	13.22
SFRC-1	200000	800	40	0.5	6.04	6.40	0.130	5.63
SFRC-1	200000	800	40	1.0	5.21	6.23	1.035	16.34
SFRC-1	200000	800	40	1.5	5.50	6.35	0.722	13.39
SFRC-1	200000	800	40	2.0	5.73	6.36	0.394	9.87
PFRC-1	7000	465	20	0.5	5.30	6.36	1.133	16.73
PFRC-1	7000	465	20	1.0	5.80	6.47	0.445	10.31
PFRC-1	7000	465	20	1.5	5.78	6.40	0.384	9.69

PFRC-1	7000	465	20	2.0	5.30	6.06	0.576	12.53
PFRC-1	7000	465	30	0.5	5.70	6.47	0.588	11.86
PFRC-1	7000	465	30	1.0	5.43	6.45	1.039	15.81
PFRC-1	7000	465	30	1.5	5.57	6.29	0.512	11.38
PFRC-1	7000	465	30	2.0	6.00	6.45	0.199	6.93
PFRC-1	7000	465	40	0.5	5.20	6.30	1.210	17.46
PFRC-1	7000	465	40	1.0	5.10	6.10	1.000	16.39
PFRC-1	7000	465	40	1.5	5.50	6.00	0.250	8.33
PFRC-1	7000	465	40	2.0	5.30	6.26	0.919	15.31
PFRC-2	7000	552	20	0.5	5.21	6.05	0.706	13.88
PFRC-2	7000	552	20	1.0	5.70	6.45	0.558	11.59
PFRC-2	7000	552	20	1.5	6.20	6.41	0.043	3.24
PFRC-2	7000	552	20	2.0	5.05	6.00	0.903	15.83
PFRC-2	7000	552	30	0.5	5.92	6.47	0.299	8.45
PFRC-2	7000	552	30	1.0	5.49	6.48	0.971	15.21
PFRC-2	7000	552	30	1.5	5.30	6.40	1.210	17.19
PFRC-2	7000	552	30	2.0	5.73	6.27	0.287	8.55
PFRC-2	7000	552	40	0.5	5.56	6.34	0.607	12.29
PFRC-2	7000	552	40	1.0	5.50	6.35	0.729	13.44
PFRC-2	7000	552	40	1.5	5.75	6.20	0.206	7.32
PFRC-2	7000	552	40	2.0	5.60	6.38	0.615	12.29
SFRC-2	200000	1150	20	0.5	5.42	6.36	0.885	14.79

SFRC-2	200000	1150	20	1.0	5.50	6.28	0.612	12.45
SFRC-2	200000	1150	20	1.5	5.50	6.22	0.520	11.60
SFRC-2	200000	1150	20	2.0	5.20	6.00	0.640	13.33
SFRC-2	200000	1150	30	0.5	5.10	6.05	0.903	15.70
SFRC-2	200000	1150	30	1.0	6.10	6.29	0.034	2.95
SFRC-2	200000	1150	30	1.5	6.30	6.29	0.000	0.20
SFRC-2	200000	1150	30	2.0	5.90	6.10	0.040	3.28
SFRC-2	200000	1150	40	0.5	6.04	6.27	0.052	3.63
SFRC-2	200000	1150	40	1.0	5.21	6.29	1.177	17.23
SFRC-2	200000	1150	40	1.5	5.50	6.29	0.622	12.54
SFRC-2	200000	1150	40	2.0	5.73	6.29	0.314	8.91
Average							0.577	11.20

This simple model for evaluating the behaviour of FRP-reinforced concrete could result in more engineers utilising this concrete form in actual applications. These results indicated that the numerical model had an adequate predictive method between input materials and output attributes.

5.5 Development of the Khan Khalel Model

The compressive and flexural strength values on various combinations of fibre input parameters have mentioned above. These results are presented in Tables 5-1 and 5-2. An empirical model has been developed based on the discussed experimental values which will help to estimate FRC properties based on material parameters such as elastic modulus, tensile strength, fibre length, and fibre percentage. MLR as discussed in section 2.4 is used to develop the model that can examine the effect of fibre characteristics on compressive and flexural strength as shown in Eq. (16) and Eq. (17). The Khan-Khalel model indicates that an increase in the length and percentage of fibre reduces the overall value of compressive strength.

$$\begin{aligned} \widehat{C.S} = & 40.72 - (1.46E - 05) \text{ Elastic modulu of fiber} + & (5-1) \\ & (4.38E - 03) \text{ Tensile strength of fiber} + \\ & (0.000604) \text{ Length of fiber} + (45.21) \text{ Percentage of fiber} \end{aligned}$$

The developed model indicates that an increase in the length and percentage of fibre can increase the overall flexural strength.

$$\begin{aligned} \widehat{F.S} = & 5.3 - (5.35E - 08) \text{ elastic modulus of fiber} + & (5-2) \\ & (1.61E + 03) \text{ Tensile strength of fiber} + \\ & (0.002656) \text{ Length of fiber} + \\ & (5.88333) \text{ Percentage of fiber} \end{aligned}$$

5.5.1 Validation of the Khan Khalel Model with Numerical Results

The developed empirical model is validated on the arbitrary input values to observe the accuracy for predicting the compressive and flexural strengths of FRC in general with the help of numerical model. We validated the model on same material types and shapes but on different lengths and percentages of

fibres. The selected values were 25mm, 35mm, 1.25% and 1.75% respectively. The obtained values of predicted compressive and flexural strengths by Khan Khalel model were compared with numerical estimations as provided in the tables 5-3 and 5-4. We have found a good agreement in between Khan Khalel and numerical models. Additionally, as shown in tables 5-3 and 5-4, mean absolute error and mean square error were used to validate the results of flexural and compressive strengths. The MSE results of the Khan Khalel and numerical model showed an error in the range of (3.84%-15%) between all flexural and compressive concrete strengths. The error in estimation of compressive strength is under 10% and hence it determines the goodness of prediction of the proposed model.

Table 5-3 Validated results for compressive strength.

Mixes of concrete	Elastic modulus of fibre types (MPa)	Tensile strength of different fibres shape (MPa)	Fibre Length (mm)	Percentage of fibre %	Compressive Strength Khan Khalel (MPa)	Compressive Strength Numerical (MPa)	(MSE) Numerical and Khan Khalel	(MAPE) Numerical and Khan Khalel
SFRC-1	200000	1150	25	1.25	43.75	47.67	15	8.93
SFRC-2	200000	800	25	1.25	41.98	45.90	15	8.75
PFRC-1	70000	465	25	1.25	42.31	45.80	12	7.61
PFRC-2	7000	552	25	1.25	43.62	45.70	4	4.56
SFRC-1	200000	1150	35	1.75	43.5	47.80	14	8.69
SFRC-2	200000	800	35	1.75	42.11	45.27	10	6.97
PFRC-1	7000	465	35	1.75	43.47	45.70	5	4.89
PFRC-2	7000	552	35	1.75	43.85	45.60	3	3.84

The MSE results of the Khan Khalel values and numerical model showed an error in the range of (0.36%-0.86%) between all flexural concrete strength output of parameters that did not use in the experimental. The error MAPE in estimation of compressive strength is under 10% and hence it determines the goodness of prediction of the proposed model.

Table 5-4 Validated results for flexural strength.

Mixes of concrete	Elastic modulus of fibre types (MPa)	Tensile strength of different type shape (MPa)	Fibres Length (mm)	Percentage of fibres (%)	Flexural Strength Khan Khalel (MPa)	Flexural Strength Numerical (MPa)	(MSE) Numerical and Khan Khalel	(MAPE) Numerical and Khan Khalel
SFRC-1	200000	1150	25	0.0125	5.62	6.49	0.76	13.42
SFRC-2	200000	800	25	0.0125	5.56	6.49	0.86	14.29
PFRC-1	70000	465	25	0.0125	5.52	6.22	0.49	11.24
PFRC-2	7000	552	25	0.0125	5.53	6.30	0.59	12.20
SFRC-1	200000	1150	35	0.0175	5.68	6.28	0.36	9.61
SFRC-2	200000	800	35	0.0175	5.62	6.49	0.76	13.40
PFRC-1	7000	465	35	0.0175	5.58	6.30	0.53	11.54
PFRC-2	7000	552	35	0.0175	5.59	6.28	0.47	10.97

As demonstrated in this study, the Khan Khalel model can predict the optimal fibre with acceptable accuracy to obtain a compressive strength adequate for usage in a structure. This straightforward method for estimating the behaviour of concrete incorporating FRP could lead to more engineers employing this form of concrete in actual applications. Compared with previous studies, the collection of investigations reveals fascinating conclusions, notably that variation in the stated test results has an accuracy (in some cases ranging from 5-15%). Moreover, This is due to extensive diversity in test specimens, materials, loading configurations, experimental methodologies, and test arrangements [339,340].

5.6 Conclusions

This chapter presented the proposed Khan Khalel model, which can be used to predict the optimal fibre reinforcement in concrete. The proposed model can take key fibre parameters as inputs and predict the compressive and flexural strengths of reinforced concrete as an output. The proposed model can facilitate the ability of users in the construction industry to select an optimal set of fibre properties during a reinforcement process. The model can be used to predict concrete behaviour with elastic fibre properties for any given physical shape and dimensions. The results show good agreement with a numerical model whereby the error represents the challenges in reinforcement, such as the ideal mixing and distribution of fibres in concrete, difficulty in finding the interfacial properties of fibres with concrete constituents, and the problem of identifying plastic behaviour using compressive and flexural testing machines.

When compared with previous studies, interesting results were obtained. The overall variation in the test results ranges from 5% to 15%. This variation is acceptable, particularly in the presence of extensive diversity in test specimens, materials, loading configurations, experimental methodologies, and test arrangements [339,340]. The empirical model prediction accuracy was measured as $R^2 = 0.997$, $MSE = 8.21$, and $MAPE = 5.93\%$, and can be used as a compressive strength prediction tool for FRC. With regard to flexural strength, models in the existing literature are able to predict with an accuracy measured as R^2 ranging from 0.78 to 0.87 and $MAPE$ ranging from 6.15 to 17.9 [341]. However, the model we presented can more accurately predict flexural strength and its accuracy is measured as $R^2 = 0.996$, $MSE = 0.64$, and $MAPE = 14.28$. The proposed model used the elastic modulus for material input selection and hence predominantly considers linear elastic behaviour in FRC during tests. However, the use of plasticity correction for this input can represent the complex non-linear relationship between the various input variables and properties of FRC. This will be considered as a change to be implemented in future work.

6 Crack Resistance Analysis of FRC

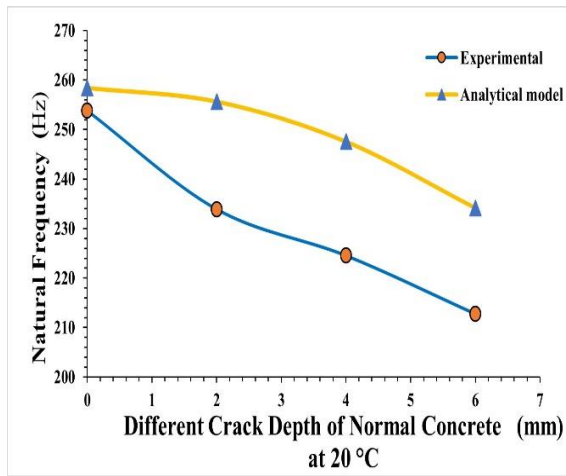
6.1 Introduction

The majority of earlier researchers reported the mechanical performance of FRC under static loads. A few studies concluded the aforementioned performance on dynamic loads. However, comprehensive analysis is still missing that can explain the crack resistance performance of FRC under dynamic loads at relatively high temperatures. In this chapter, the efficacy of FRC beams in terms of crack resistance is analysed under coupled loads, i.e., dynamic loads at relatively high temperatures. Cantilever FRC beams were tested on a modal exciter in a band heater to expose the beams to bending loads at different temperature values. The variation in the dynamic response parameters of the beams, including modal amplitude and frequency, is discussed and compared with the experimental results for regular and reinforced concrete beams. The stress intensity factor (SIF) and displacement amplitude characteristics show that the SFRC specimens have excellent ductile behaviour and higher crack resistance than ordinary concrete samples.

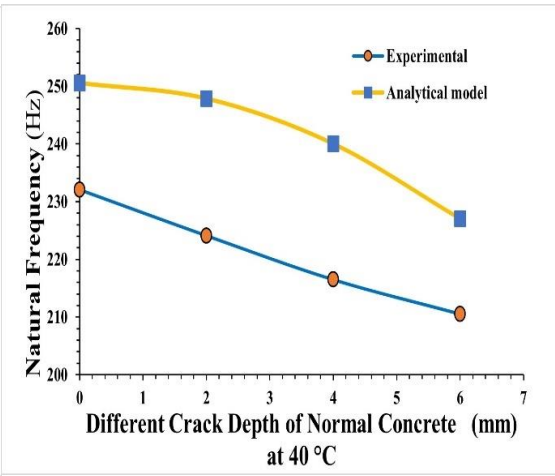
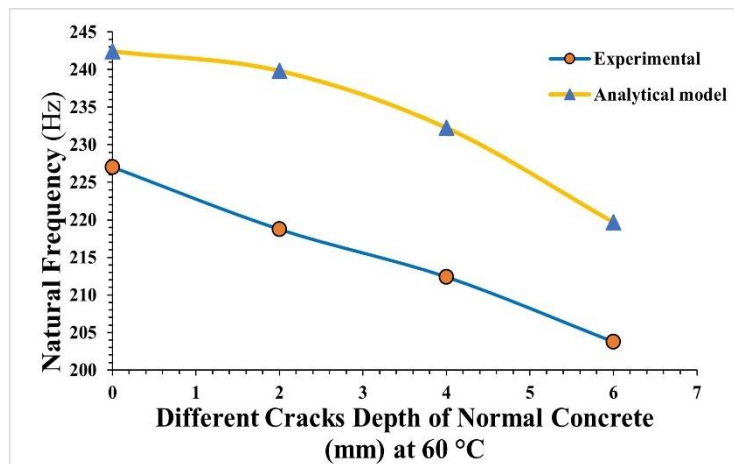
6.2 Cantilever Beam End Mass System Dynamic Response

Section 3.6.3 describes the fatigue tests on beams with various crack depths and temperatures. The original and adjusted stiffness values were used to create dynamic response models. The analytical model used Equation (3-30) to calculate the elastic modulus values at various temperatures. Figures 6-1 and 6-2 below show the beam's fundamental frequency of the control concrete and the SFRC at the beam tip; the experimental displacement amplitudes of the standard concrete and SFRC are shown in Figures 6-3 and 6-4 for the various crack depths. The maximum number of intervals in MATLAB R2019b was surpassed by 2.7 mm when the crack depth was measured at the 5 mm crack location, resulting in approximations that fell short of the desired level of accuracy. The fitted curves for the fundamental frequency were plotted based on the analytical results for crack depths ranging from 0 to 6 mm.

(a)



(b)



(c)

Figure 6-1 Natural frequency of normal concrete measured experimentally and predicted using an analytical model at various crack depths and temperatures.

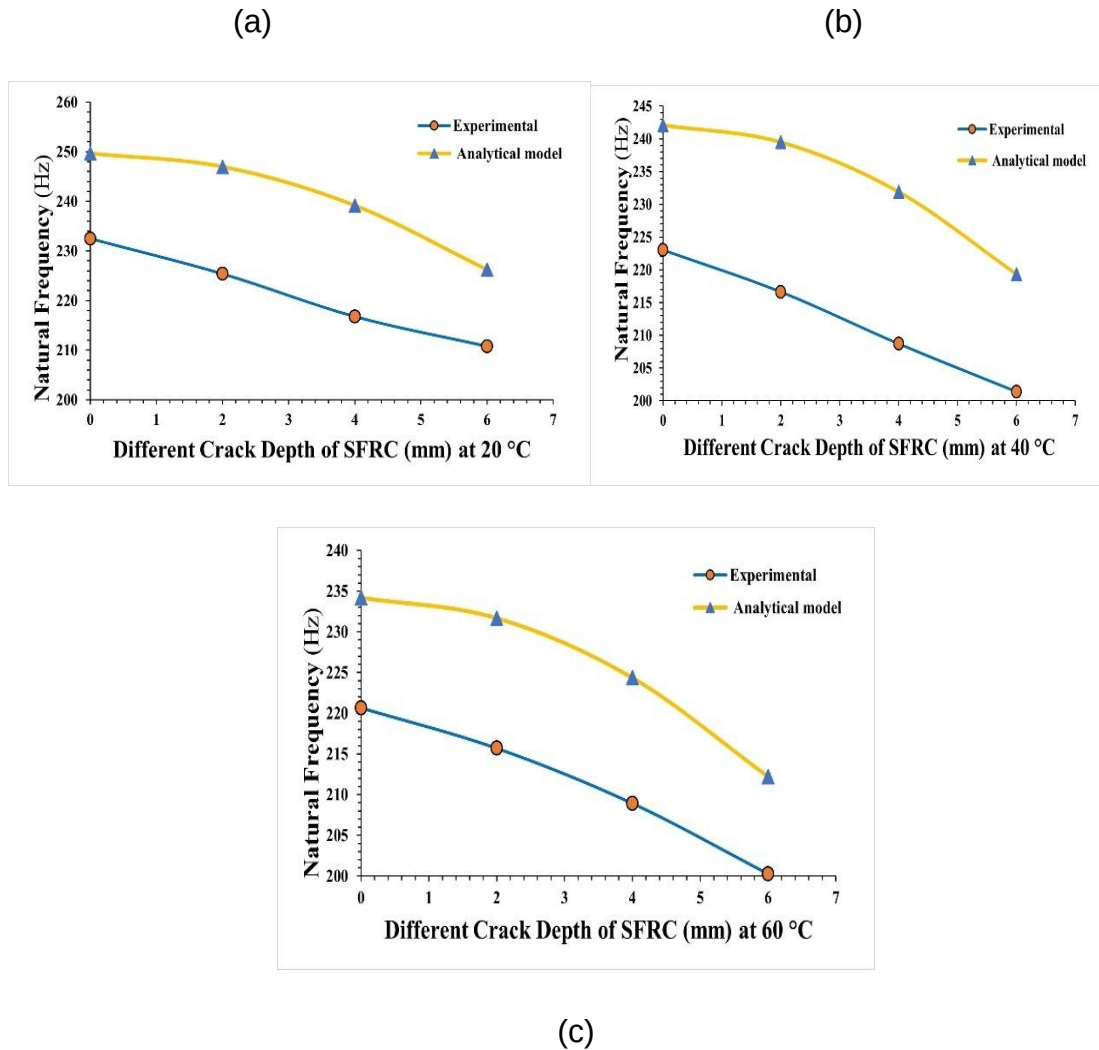


Figure 6-2 Natural frequency of SFRC measured experimentally and predicted using an analytical model at various crack depths and temperatures.

6.3 Fundamental Frequency of the Seeded Crack Beams

6.3.1 Influence of Crack Depth on the Fundamental Frequency of Normal Concrete and SFRC

Figures 6-1 and 6-1 show the results of the impact of crack depth on the natural frequency of cantilever concrete beams with and without steel fibres. Natural frequency and dynamic characteristics are among the essential aspects of construction and are frequently employed, such as for the long-term assessment of bridges over their service life. The relationship between crack depth and a

change in fundamental frequency at an ambient temperature of 40 °C at a 5 mm crack location was considered for analysis because the analytical model and experimental data show similar trends for a change in fundamental frequency with crack depth at ambient temperature. There is a gradual decrease in the frequency of samples with differences in crack depth. The experimental results indicated a 7.84% decrease in frequency when the crack depth in the standard concrete was 2 mm. In addition, the results indicate that the natural frequency of SFRC decreased by about 9% when the steel fibre was added to the concrete beam at the same crack depth. The results showed a slight decrease in the natural frequency of ordinary concrete from 0 mm (253.776 Hz) to 6 mm (212.702) cracking of the beam, about 16.174%. However, the frequency of the SFRC beam gradually decreased to about 9.35%. As a result, the frequencies of the standard concrete and the SFRC were shown to decrease when the crack depths increased. The reduction in natural frequency values observed for the beam's containing fibre was less due to their being induced by a seeded crack, compared with the control reinforced concrete (RC) beam. Furthermore, the Khan model of RC beams reinforced with steel fibres Khan-He has completed the beams' uncracked and cracked beam conditions.

Crack depths are shown in Figure 6-1 by plotting the fundamental frequency and drop percentage change as predicted by the Khan-He model and data from the experiments. The experimental data and analytical model (see Figures 6-1 and 6-2) show that the fundamental frequencies of the normal concrete and the SFRC decrease as the crack depth increase. The fundamental frequency of the control concrete lowers from around 212.72 Hz to 203.7 Hz at a crack depth of 6 mm compared to an entire 25 mm-thick beam, which is just 4.2% of the initial fundamental frequency. Analytical models show that the local drop-in stiffness owing to increased crack depth reduces the stiffness matrix, resulting in a gradual fall in the fundamental frequency.

Notably, the fundamental frequency change is minimal when there is no crack on the surface of the beam. However, when the crack depth of the beam increases, the fundamental frequency decreases. For example, when a 4 mm (one-sixth of

the beam thickness) crack is present in the ordinary concrete beam, the frequency decreases by approximately 16 Hz (7% relative change); in contrast, the frequency decreases by around 14 Hz (6% relative change) from the 4 mm crack depth of the FRC beam. In other words, sensitive sensors are necessary when employing crack depth to forecast fundamental frequency.

In general, SFRC frequency is lower than that of conventional concrete. Furthermore, fibre has a negative effect on frequency. As indicated by the data, when the crack depth increases, the frequency decreases. Cracks affect the fatigue lives and limits of concrete and SFRC beams. Thus, crack depth would degrade the fatigue behaviour of the reinforced beams.

6.3.2 Influence of Temperature on the Fundamental Frequency of Normal Concrete and SFRC

Figures 6-1 and 6-2 demonstrate the impact of temperature on the natural frequency of cantilever concrete beams with and without steel fibres. There is a gradual decrease in the frequency of the samples with differences in crack depth. The experimental results indicated a 7.84% decrease in frequency when the temperature of the standard concrete was 40 °C. In addition, the results suggest that the natural frequency of SFRC decreased by about 9% when the steel fibre was added to the concrete beam at the same temperature. The results showed a slight decrease in the natural frequency of ordinary concrete without cracks from 20 °C (253.776 Hz) to 60 °C (226.9 Hz) in the beam (about 10.5%). However, the frequency of the SFRC beam without cracking gradually decreased from 20 °C (232.5 Hz) to 60 °C (220.65 Hz) (about 5.08%). This indicates that the frequency of the standard concrete and the SFRC decreased when the temperature increased. According to previous findings, it is widely accepted that the concrete elastic modulus, geometrical features, constraints, and boundary conditions of construction applications are changed by temperature, which causes variations in fundamental frequencies.

Various studies show that temperature is the most significant environmental element influencing structural vibration [342,343], and that its influence may be higher than that of structural damage [344]. Xia et al. examined the change of

modal frequencies against non-uniform temperature distribution for an RC slab by considering the correlations between natural frequencies and temperature. It was amply demonstrated that when temperature increased, natural frequencies decreased [345]. Li et al. found that high temperatures reduced SFRC elastic modulus while increasing its critical strain, and that peak toughness increased initially and then decreased as the temperature rose [346]. The highest value was observed in the frequency of standard concrete at 20 °C. This is related to plasticity formation at lower temperatures and ductility at higher temperatures. When the modal variability generated by daily temperature differences and seasonal temperature fluctuations are coupled, it has a complex influence on structural applications such as bridge construction, dams, and highways. Furthermore, the temperature in the SFRC reached 60 °C at the same time, which is the temperature that causes stiffness reduction. As a result, the change in displacement slope observed after approximately 30 min of heating is also related to the greater deformability of an unreinforced beam at ambient temperature. The frequency of concrete was decreased for two reasons. The first was due to the increase in the temperature, and the second is that the elastic modulus of concrete is slightly impacted by the 1% volume fractions of steel fibres used in this study. However, the elastic modulus of SFRC is anticipated to decrease as more fibres are added. In addition, it is seen that the natural frequency of fibre decreases as the fibre volume fraction increases, which other researchers have demonstrated [347].

In general, SFRC frequency is lower than that of conventional concrete. Furthermore, fibre has a negative effect on frequency. When the temperature increases, as indicated by the data, a decrease in frequency is revealed. Temperature affects the fatigue lives and limits of concrete and SFRC beams. Therefore, high temperature environments would degrade the fatigue behaviour of reinforced beams.

6.4 Influence of Crack Depth on Displacement Amplitude

The displacement amplitude of beams with fibre and without fibre at 0.0 mm, 2 mm, 4 mm, and 6 mm crack depths at different temperatures was examined to

compare the trends of the displacement amplitude of the samples at the three crack depths. Figures 6-3 and 6-4 show the variation in displacement amplitude of the control and SFRC beams with different crack depths. At crack depths of an ordinary concrete beam of 0 mm to 6 mm, the displacement amplitude drops from roughly 0.0034 mm. Similarly, the drop for the reinforced concrete was from 0 mm to 6 mm; about 0.0042. However, the displacement of the SFRC was higher than that of the standard concrete. For example, at crack depths of 2 mm, 4 mm, and 6 mm, the displacement of the ordinary concrete and the SFRC at 40 °C was (0.0132, 0.0124, 0.0117, 0.0104 mm) and (0.0140, 0.0136, 0.0125, 0.0105 mm), respectively. Moreover, the change in displacement amplitude is as gradual as the crack depth at the top surface of the beam. When the crack depth of the beam is 6 mm, the displacement amplitude falls sharply.

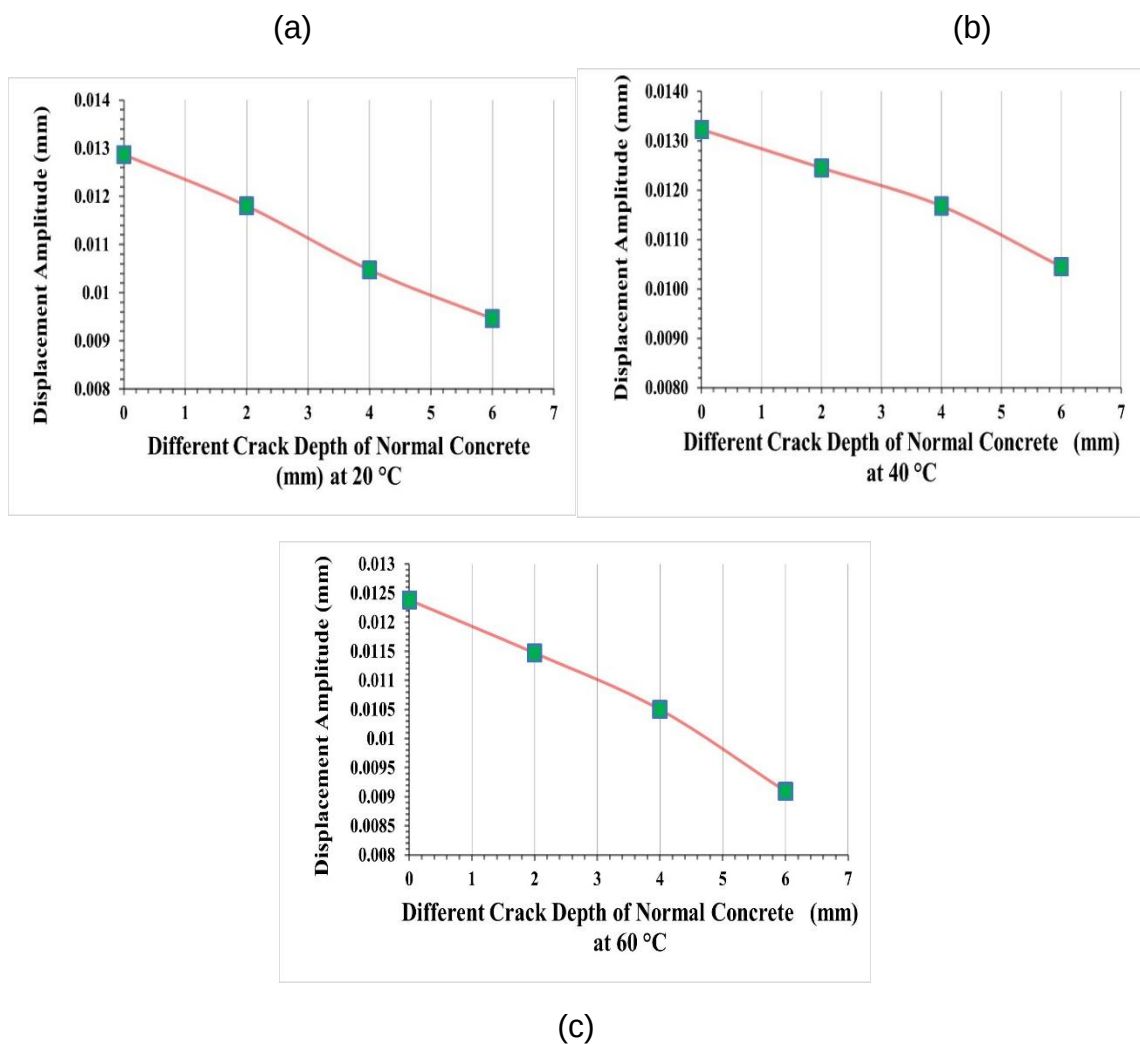


Figure 6-3 Displacement amplitudes of normal concrete measured experimentally at various crack depths and temperatures.

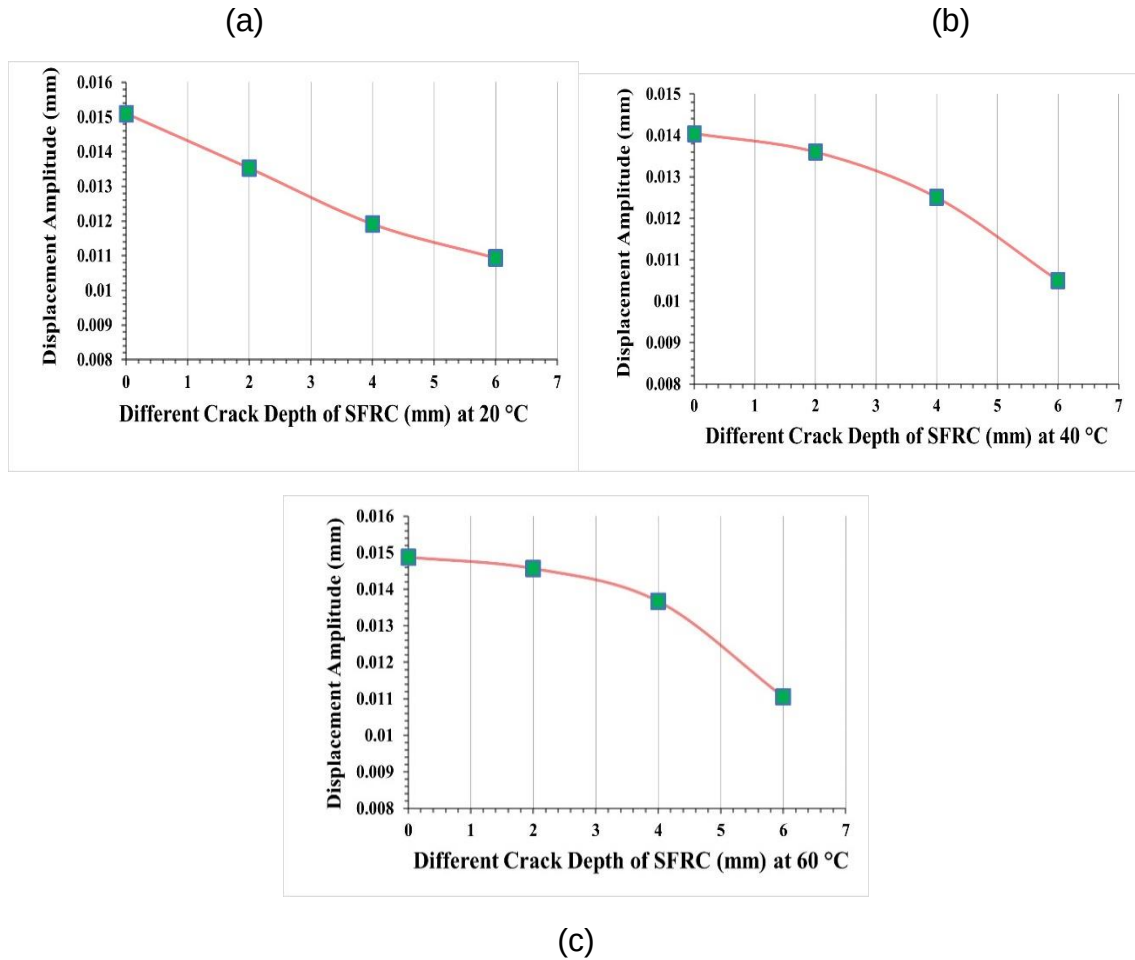


Figure 6-4 Displacement amplitudes of SFRC measured experimentally at various crack depths and temperatures.

The decrease in beam displacement amplitude with an increase in crack depth can be ascribed to two factors. First, as the fracture depths increase, the load required to maintain the displacement amplitude of FRC steadily reduces. In other words, the force pushing on the beam reduces gradually. Reduced stress leads to smaller displacement amplitudes. Second, an increasing crack depth enhances beam damping. As a result, the energy released by damping during vibration increases, whereas the displacement amplitude decreases.

In general, SFRC displacement is more than that of conventional concrete. Furthermore, fibre has a positive effect on displacement. When a crack increases, as indicated by the data, a decrease in displacement is revealed. Crack depths affect the fatigue lives and limits of concrete and SFRC beams. Therefore, increasing cracks would degrade the fatigue behaviour of the reinforced beams.

6.5 Influence of Temperature on Displacement Amplitude

Figures 6-3 and 6-4 show how temperature affected the displacement amplitude of beams with and without steel fibre. The impact of various temperatures on the displacement amplitude of cracked beams is complex, in contrast to all prior response trends. The displacement amplitude of a beam from an intact to a cracked condition is at its lowest at 20 °C, as indicated in Figure 6-3. at 20 °C, the entire beam has the maximum displacement amplitude but, when the temperature increases, the displacement decreases. The displacement of the SFRC beam was higher than that of the beam without fibre. For example, the displacement of different beams with and without fibre at different crack depths (2 mm, 4 mm, 6 mm) at the same temperature of 40 °C was (0.01245, 0.0117, 0.0104) and (0.0136, 0.0125, 0.0105), respectively. This incidental phenomenon supports the experimental findings of earlier studies [1]. Greater seasonal temperature variations than a dam has previously experienced appear to be more likely to affect its concrete temperature and relative displacement [348]. These phenomena are explained explicitly by the interaction of temperature-dependent excitation loads and variable elastic moduli. When the temperature increases and the beam is exposed to the same external excitation, the overall flexibility of the beam naturally decreases, and the displacement amplitude gradually increases. However, the fundamental frequency decreases in relation to the temperature increase. As a result, the external forces imposed on the beam reduce the displacement amplitude and frequency, lowering the beam displacement amplitude. The overall response of the displacement amplitude of the beam loses monotonicity and becomes more complex because of these two conflicting impacts.

The outcomes above demonstrate a favourable impact of steel fibre particles when applied to dynamic loading, including displacement with exposure to various temperatures (20, 40, 60 °C). Steel softens and eventually decomposes at different temperatures, so the enhanced effect of SFRC on frequency diminishes after it undergoes a high-temperature treatment.

In general, the displacement of plain and FRC decreases with an increase in concrete temperatures. SFRC displacement is more than that of conventional concrete. Furthermore, fibre has a positive effect on displacement. When the temperature increases, as indicated by the data, a decrease in displacement is revealed. Temperatures affect the fatigue lives and limits of concrete and SFRC beams. Therefore, increasing temperatures would degrade the fatigue behaviour of the reinforced beams. As a result, the thermal impacts must be considered when designing concrete structures for safety.

6.6 Calculation of Stress Intensity Factor and Crack Resistance

Structural behaviour against crack propagation is quite significant for concrete applications. The stress intensity factor represents the crack resistance and fracture toughness of a material [349,350]. Some researchers said that the interaction between the SIFs at the crack's tip symbolizes the conflict between the forces working to open and close the crack: the cohesive force and the crack driving force. Therefore, the concrete's crack resistance qualities should be considered when determining the equilibrium condition of the SIFs at the crack tip [351,352]. In this study, the stress intensity factor of beams with and without fibre at 2 mm, 4 mm, and 6 mm crack depths at different temperatures was calculated. Figures 6-5 shows the stress intensity factor variation of the control and SFRC beams with different crack depths. At crack depths of an ordinary concrete beam of 0 mm to 6 mm, the crack resistance was lower than SFRC at 20°C, 40°C, and 60°C. For example, at crack depths of 2 mm, 4 mm, and 6 mm, the crack resistance of the ordinary concrete and the SFRC at 40 °C was (0.344,0.422,0.463) MPa m^{-1/2} and (0.386,0.546,0.536) MPa m^{-1/2}, respectively. Moreover, the change in resistance is as gradual as the crack depth at the top surface of the beam. These observations are comparable with previous research where fibre impacts on concrete toughness were found more significant in the tearing mode than in the tension mode.

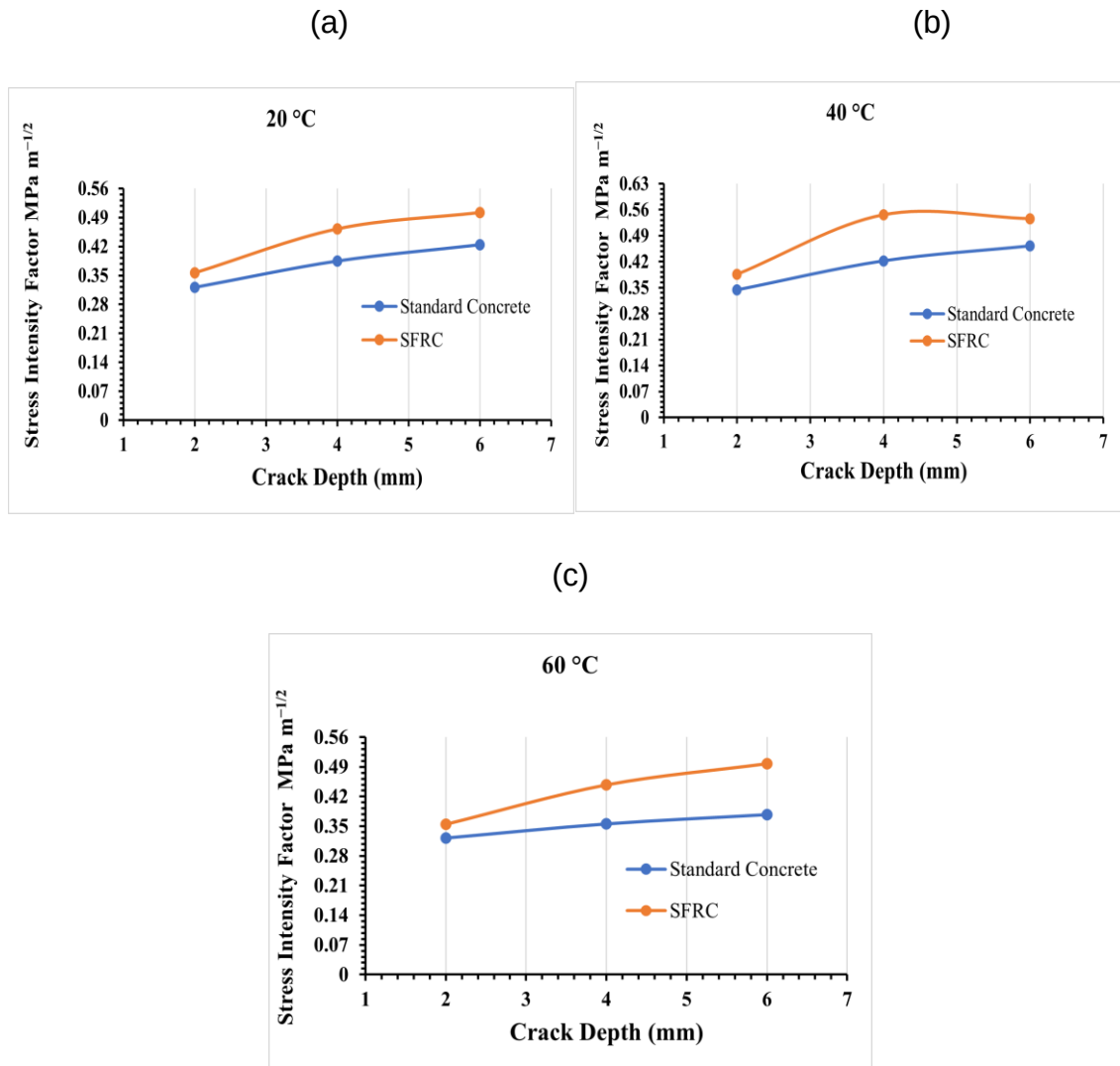


Figure 6-5 Concrete stress intensity factor with and without steel fibre at various crack depths (mm) and temperatures.

In general, the SIF of plain concrete decreases with increased concrete temperatures. However, there is no temperature impact on the SIF of steel fibre reinforced concrete beam. In addition, it was observed that the SIF of a concrete beam with reinforcement reduces as crack length increases. As a result, unstable crack propagation lowers its load-carrying capacity but does not result in the beam being destroyed quickly [353].

6.7 Comparison and Evaluation of Fundamental Frequency Variations

Experimental data and analytical model outputs of the fundamental frequencies of standard concrete and SFRC for different crack depths and temperatures are shown in Figures 6-1 and 6-2. The fundamental frequency of the specimens decreases as the seeded crack depth increases, according to the experimental results and the calculations of the analytical model. A similar result was found previously [1]. The fundamental frequencies of standard concrete and SFRC were determined using an identical model, as shown by a comparison of the results of the analytical model-based fundamental frequency calculations. The basic frequency curve of the original spring stiffness model tends to decrease as the crack depth increases. In contrast, the modified spring stiffness model drops rapidly and decreases even more rapidly as the crack depth increases. At a temperature of 60 °C of the concrete without steel fibres, the fundamental frequency results of the experimental and modelling results were 227 Hz at zero depth, 218.726 Hz at 2 mm, and 203.8 Hz at 6 mm. This is due to increases in the seeded crack depth and the temperature rises. From 0 to 6 mm fracture depth, the results of the experiment show a slight increase from 6.4 to 7.23% in terms of percentage proportion to the original stiffness model.

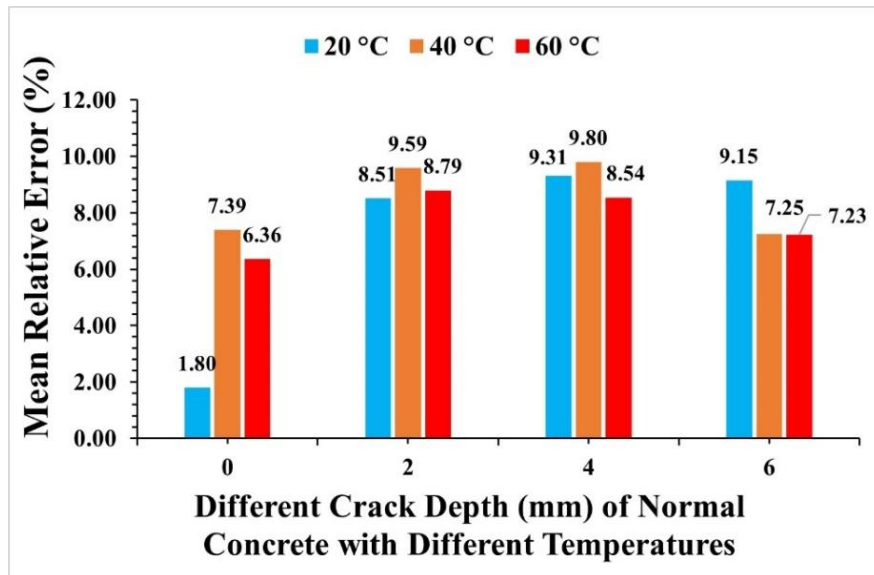


Figure 6-6 Relative variance between the analytical model and experiment results of normal concrete.

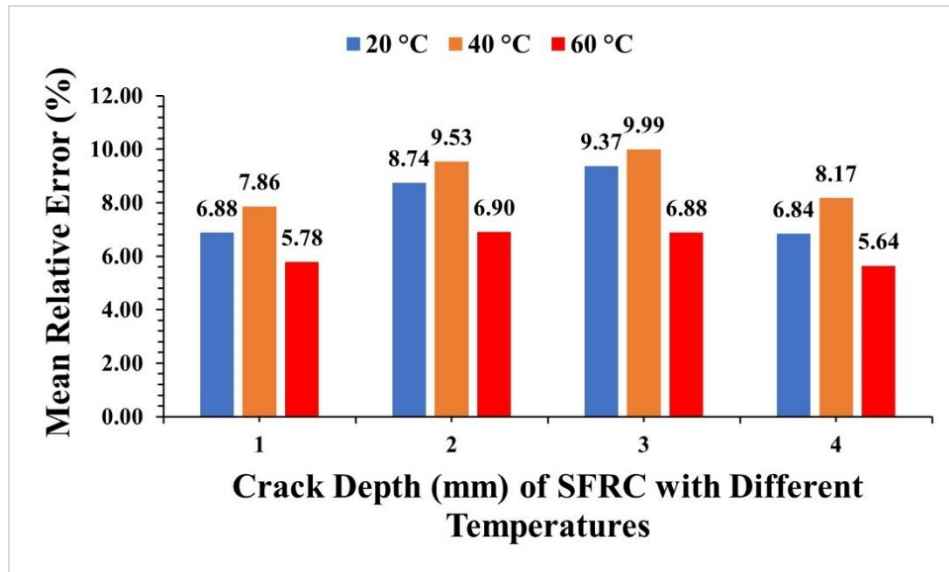


Figure 6-7 Relative variance between the analytical model and experiment results of SFRC.

Section 3.2 reported the spring model of crack depth and the difference in the fundamental frequency of crack depths. It was originally assumed that the stress field and surface stresses of bending beam cracks were of equal size in the spring stiffness modelling process. It is only possible to use this estimate for shallow cracks near the surface of a beam. Stress errors increase as the crack depth increases. There are two different terms in the suggested Khan-He model that ensure that the stiffness coefficient of the spring is zero when a beam is cracked. When comparing the results of the analytical model with the experimental data, it becomes clear that the model's projected values, particularly at high crack depths, can be accepted. As shown in Figures 6-1 and 6-2, the experimental data and the spring stiffness model have significant disparities. Temperatures and crack depths have varying fundamental frequencies. Furthermore, the variation in the fundamental frequency with crack depth is consistent across all plots. A crack depth at 2 mm under 40 °C at the 5 mm crack position is shown. There are signs of good argument between the results of the different crack depth tests, which are summarised here. Figures 6-6 and 6-7 depict the differences between the analytical and experimental findings produced using the analytical model, as shown by the relative difference. The fundamental frequencies computed using the Khan-He Model and the experimental results for different fracture depths grow

increasingly dissimilar as the crack depth increases. When crack depths ranging from 2 mm to 6 mm are applied, the Khan-He model produces fundamental frequencies within 10% of the experimental data. Compared to crack depths of 2 mm and 6 mm, the variation in fundamental frequency is just 8.74% and 5.64%, respectively. The fundamental frequency of the analytical model was determined using a second-order polynomial fit because the precision of the MATLAB approach was insufficient. The use of this fit likely contributed to the 10% disparity between the value and the experimental data.

There are signs of good arguments between the results of the different crack depth tests, which are summarised here. Figures 6-6 and 6-7 depict the difference between the analytical and experimental findings produced using the analytical model, as shown by the relative difference. The fundamental frequencies computed using the Khan-He Model and the experimental results for different fracture depths become increasingly dissimilar as the crack depth increases. When crack depths ranging from 2 mm to 6 mm are applied, the Khan-He model produces fundamental frequencies within 10% of the experimental data. Compared to crack depths of 2 mm and 6 mm of SFRC, the variation in fundamental frequency is just 0.08% and 0.07%, respectively. The analytical model fundamental frequency was determined using a second-order polynomial fit because the precision of the MATLAB approach was insufficient. The use of this fit likely contributed to the 10% disparity between the value and the experimental data.

In general, the values of the fundamental frequencies predicted by the Khan-He model matched those observed in the experiments. The fundamental frequency response of the beam may be accurately estimated for specified crack depths, compared to the experimental results.

6.7 Conclusions

In this chapter, the efficacy of FRC beams for fracture resistance was investigated under coupled loads, i.e., dynamic loads at relatively high temperatures. Cantilever FRC beams were subjected to bending loads at various temperature levels using a modal exciter in a band heater. The variation in the dynamic

response parameters of the beams, such as modal amplitude and frequency, was examined and compared with experimental data for regular and reinforced concrete beams. The findings of this investigation are as follows:

- The results showed a slight decrease in the natural frequency of ordinary concrete from 0 mm (253.776 Hz) to 6 mm (212.702) cracking of the beam (16.174%). However, the frequency of the SFRC beam gradually decreased to approximately 9.35%. As a result, the frequencies of the standard concrete and the SFRC decreased when the crack depths increased.
- In the present study, the temperature level affected the natural frequency of both the unreinforced concrete and the FRC. The findings show that the natural frequency of SFRC samples was lower than the typical frequency of concrete. Furthermore, the results showed a slight decrease in the natural frequency of ordinary concrete without cracks, from 20 °C (253.776 Hz) to 60 °C (226.9 Hz) in the beam (about 10.5%). However, the frequency of the SFRC beam without cracking decreased gradually, from 20 °C (232.5 Hz) to 60 °C (220.65 Hz) (about 5.08%). As a result, the frequency of the standard concrete and the SFRC decreased when the temperature increased.
- Temperatures affect the fatigue life of concrete and SFRC beams. Therefore, higher temperatures would degrade the fatigue behaviour of reinforced beams.
- The displacement of the SFRC was higher than that of the standard concrete. For example, at crack depths of 2 mm, 4 mm, and 6 mm, the displacement of the ordinary concrete and the SFRC at 40 °C was (0.0132, 0.0124, 0.0117, and 0.0104 mm) and (0.0140, 0.0136, 0.0125, and 0.0105 mm), respectively. Moreover, the change in displacement amplitude was as gradual as the crack depth at the top surface of the beam. When the crack depth of the beam was 6 mm, the displacement amplitude fell sharply.

- The displacement of the SFRC beam was higher than that of the beam without fibres. For example, the displacement of different beams with and without fibre at different crack depths (2 mm, 4 mm, and 6 mm) at the same temperature of 40 °C was (0.01245, 0.0117, and 0.0104) and (0.0136, 0.0125, and 0.0105), respectively. As a result, fibre has a positive effect on displacement.
- The values of the fundamental frequencies predicted by the Khan-He model matched those observed in the experiments. The fundamental frequency response of the beam may be accurately estimated for specified crack depths compared with the experimental results. When crack depths ranging from 2 mm to 6 mm were applied, the Khan-He model produced fundamental frequencies within 10% of the experimental data. Compared with crack depths of 2 mm and 6 mm for SFRC, the variation in fundamental frequency was just 0.08% and 0.07%, respectively.
- The SIF and displacement amplitude characteristics show that SFRC specimens have excellent ductile behaviour and crack resistance compared with ordinary concrete samples. The SIF of plain concrete decreased with an increase in concrete temperature. However, there was no significant temperature impact on the SIF of SFRC beams. For example, the crack resistance was increased by using SFRC-1 by about 10-20% at different crack depth (2mm,4mm,6mm) temperatures (20 °C,40°C,60°C) compared with standard concrete.

7 Conclusions and Future Investigation

7.1 Achievement of Objectives

The fundamental aim of this study was to investigate the mechanical behaviour of concrete structures under thermo-mechanical dynamic loads in the presence of reinforcing fibres of different weight ratios. The research had the following five objectives.

7.1.1 To review the effect of fibres, including steel, plastic and waste materials, on concrete performance

To achieve the first research objective, a comprehensive literature review was conducted, and the results are discussed in detail in Chapter 2. The literature review presented a critical analysis of previous research studies emphasizing the optimization of FRC to improve its strength against various load regimes, with a particular emphasis on coupled load conditions. The preamble in Chapter 2 presents the historical context, a description of the evolution of concrete as a material for advanced structures, such as multi-storey buildings, dams, bridges, industrial structures, retaining walls, and hydraulic and marine structures, and the basic principles of concrete production. The literature review also discusses FRC, fibre types and shapes, mixing methods, and the testing of the properties of concrete. In addition, the literature review considers how the mixing of fibres can influence fatigue and fracture behaviour, particularly under different load regimes.

In conclusion, the literature review presented in Chapter 2 identifies research gaps and potential new directions for investigation. The review reveals that performance estimations of concrete structures subjected to coupled loads have received little consideration. It is anticipated that the unresolved issues in fibre reinforcement will result in a complex zone of empirical findings if the selected structures are tested under coupled load conditions.

7.1.2 The optimization of reinforced fibres in concrete.

To achieve the second research objective, extensive mechanical and fresh tests were performed to optimize the mechanical properties of conventional concrete and were used to develop an optimization method based on parametric analysis for the optimization of FRC to find an optimal fibre value for reinforced concrete. The Khan Khalel model was proposed to predict the optimal fibre reinforcement in concrete. The proposed model can take key fibre parameters as inputs and predict the compressive and flexural strengths of reinforced concrete as outputs. The Khan Khalel model can facilitate users in the construction industry when selecting an optimal set of fibre properties during the reinforcement of concrete. The model can predict concrete behaviour with elastic fibre properties and any given physical shape and dimensions. The results presented show good agreement with the Khan Khalel model, whereby errors represent the challenges in reinforcement, such as the ideal mixing and distribution of fibres in concrete, difficulty in finding the interfacial properties of fibres with concrete constituents, and problems relating to finding plastic behaviour using compressive and flexural testing machines.

7.1.3 To validate the optimization by testing a concrete structure under conventional quasi-static loads and create an empirical model of the impact of reinforcing fibres on concrete mechanical behaviour and validation

To achieve the third and fourth research objectives, the empirical model was used to predict the optimal fibre reinforcement in concrete. The proposed model can take key fibre parameters as inputs and predict the compressive and flexural strengths of reinforced concrete as outputs. The proposed model can facilitate users in the construction industry in selecting an optimal set of fibre properties during reinforcement. Furthermore, the model can predict concrete behaviour with elastic fibre properties and any given physical shape and dimensions. The results presented show good agreement with the numerical model, whereby errors represent the challenges in reinforcement, such as the ideal mixing and distribution of fibres in concrete, difficulty in finding the interfacial properties of

fibres with concrete constituents, and problems relating to finding plastic behaviour using compressive and flexural testing machines.

7.1.4 To investigate the impact of fibres on the mechanical behaviour of concrete under thermo-mechanical dynamic loads

To accomplish the fifth research objective, the efficacy of FRC beams for crack resistance was analysed under coupled loads, i.e., dynamic loads at relatively high temperatures. Cantilever FRC beams were tested on a modal exciter in a band heater to expose the beams to bending loads at different temperature values. The variation in the dynamic response parameters of the beam, including modal amplitude and frequency, was discussed and compared with the experimental results for regular and reinforced concrete beams. The results presented show that the SIF and displacement amplitude characteristics of the SFRC specimens had excellent ductile behaviour and crack resistance compared with the ordinary concrete samples. The SIF of plain concrete decreased with an increase in concrete temperatures. However, there was no significant temperature impact on the SIF of SFRC beams.

7.2 Contributions

The literature review highlighted the key gaps and unaddressed challenges related to optimizing concrete reinforcement with different types of fibre under various load regimes. Three key contributions were achieved by the current study.

7.2.1 Parametric Study for Optimizing FRC Properties

The majority of the previous researchers in this area did not consider the combination of percentages, types, and shapes of fibres in their studies in order to find the optimal values for enhancing the properties of concrete. Analysis is still required to find the optimum addition of fibres for desirable concrete performance. The mixing of fibres has its own challenges, and it is essential to consider these when deciding the optimum addition of fibres. This study demonstrated the use of parametric analysis to find the optimal shape, size, and percentage of fibres.

The design variables for optimization were divided into input and output parameters. The input parameters were the influences of type, length, and percentage of fibres on concrete performance, including samples of fresh and mechanical concrete properties. In order to search for the best relation of fibre dose and dimension to optimize the combined responses of workability and splitting tensile, flexural, and compressive strengths, tests were carried out on the fresh and mechanical properties of concrete reinforced with four different fibres: PFRC-1, PFRC-2, SFRC-1, and SFRC-2. The analysis results concluded that among the mixes tested, the optimal mix was SFRC-2-20mm-1% with respect to compressive, split tensile, and flexural strengths, as well as workability. The optimization method used in this study provides new critical insight into the relationship between output and input parameters.

7.2.2 Modelling FRC to Predict Optimal Mechanical Properties

The selection of fibre material for this type of reinforcement is always challenging, as it is mainly dominated by the properties required at the construction site. Materials such as steel and plastic fibres are now rigorously used due to their mechanical properties. Academic researchers have comprehensively discussed the impact and challenges of fibre reinforcement to obtain optimal properties for the resultant concrete. However, most of this research concludes its analysis without considering the collective influence of key fibre parameters, such as the shape, type, length, and percentage of the materials added. There is still a need for a model that can consider these key parameters as inputs and provide the properties of reinforced concrete as outputs, and to facilitate the user in analysis of the optimal fibre addition as per the construction requirements. The current work proposes the Khan Khalel model, which can predict the desirable compressive and flexural strengths for any given values of key fibre parameters. Statistical tools were used to develop and validate the model with numerical results. The proposed model is easy to use but predicts compressive and flexural strengths with errors under 6% and 15%, respectively. This error primarily represents the assumption made for the input of fibre material during model development. It is currently based on the elastic modulus of the material and

hence neglects the plastic behaviour of the fibre. A possible modification in the model for considering the plastic behaviour of the fibre will be considered in future work.

7.2.3 Dynamic Response-based Crack Resistance Analysis of FRC Beams under Different Temperatures and Crack Depths

Academic researchers have comprehensively discussed the impact and challenges of fibre reinforcement to obtain optimal properties in the resultant concrete. Most of the researchers reported the mechanical performance of FRC under static loads. A few studies concluded the aforementioned performance in respect of dynamic loads. However, a comprehensive analysis is still missing that can explain the crack resistance performance of FRC under dynamic loads at relatively high temperatures. This study demonstrated the efficacy of FRC beams for crack resistance analysed under coupled loads, i.e., dynamic loads at relatively high temperatures. Cantilever FRC beams were tested on a modal exciter in a band heater to expose the beams to bending loads at different temperature values. The variation in the dynamic response parameters of the beam, including modal amplitude and frequency, was discussed and compared with the experimental results for regular and reinforced concrete beams. The SIF and displacement amplitude characteristics show that the SFRC specimens demonstrated excellent ductile behaviour and higher crack resistance than the ordinary concrete samples.

7.3 Future Work

Future work could further expand the scope of FRC in respect of the Khan Khalel model and improve its accuracy. The proposed model used the elastic modulus for material input selection and predominantly considered linear elastic behaviour in FRC during tests. However, plasticity correction in this input could represent the complex non-linear relationship between the various input variables and properties of FRC. This error primarily represents the assumption made for the input of fibre material during model development. This is based on the elastic modulus of the material and hence neglects the plastic behaviour of the fibre. A possible modification in the model for considering the plastic behaviour of fibre

will be considered as future work. In addition, the validation was compared with the numerical model without experimental confirmation because of the time limitation for samples of different lengths and percentages to verify the accuracy of this model. This will be considered as a change to be implemented in future work.

The dynamic response and crack resistance were calculated using the optimal value of fibre achieved in Chapter 3, without considering the fibre distribution in the concrete because this was random. For this reason, we recommend considering fibre distribution in future study.

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APPENDICES

Appendix 1 Concrete mix design

Concrete mix design

Blank mix design form:

Table 1 Concrete mix design form

Job title

Stage	Item	Reference or calculation	Values																				
1	1.1 Characteristic strength	Specified	30 N/mm^2 N/mm ² at 28 days																				
	1.2 Standard deviation	Fig 3	Proportion defective 8 N/mm ² or no data N/mm ²																				
	1.3 Margin	C1 or Specified	$(k = 1.64) \times 1.64 \times 8 = 13.12 \text{ N/mm}^2$																				
	1.4 Target mean strength	C2	$30 + 13 = 43 \text{ N/mm}^2$																				
	1.5 Cement strength class	Specified	42.5/52.5																				
	1.6 Aggregate type: coarse Aggregate type: fine		Crushed/uncrushed Crushed/uncrushed																				
	1.7 Free-water/cement ratio	Table 2, Fig 4	0.52																				
	1.8 Maximum free-water/cement ratio	Specified	0.56																				
			Use the lower value 0.54																				
2	2.1 Slump or Vebe time	Specified	Slump 30-60 mm or Vebe time s																				
	2.2 Maximum aggregate size	Specified	213.24 mm																				
	2.3 Free-water content	Table 3	kg/m ³																				
3	3.1 Cement content	C3	$213.24 \div 0.54 = 427 \text{ kg/m}^3$																				
	3.2 Maximum cement content	Specified	kg/m ³																				
	3.3 Minimum cement content	Specified	kg/m ³																				
			use 3.1 if ≤ 3.2 use 3.3 if > 3.1																				
	3.4 Modified free-water/cement ratio		kg/m ³																				
4	4.1 Relative density of aggregate (SSD)		2.7 known/assumed																				
	4.2 Concrete density	Fig 5	kg/m ³																				
	4.3 Total aggregate content	C4	$2380 - 213.34 - 427 = 1740 \text{ kg/m}^3$																				
5	5.1 Grading of fine aggregate	Percentage passing 600 µm sieve	60 %																				
	5.2 Proportion of fine aggregate	Fig 6	41 %																				
	5.3 Fine aggregate content	C5	$0.39 \times 1740 = 679 \text{ kg/m}^3$																				
	5.4 Coarse aggregate content		$1740 - 679 = 1061 \text{ kg/m}^3$																				
<table border="1"> <thead> <tr> <th>Quantities</th> <th>Cement (kg)</th> <th>Water (kg or litres)</th> <th>Fine aggregate (kg)</th> <th>Coarse aggregate (kg)</th> </tr> <tr> <th></th> <th></th> <th></th> <th>10 mm</th> <th>20 mm</th> </tr> </thead> <tbody> <tr> <td>per m³ (to nearest 5 kg)</td> <td>427</td> <td>213</td> <td>679</td> <td>1061</td> </tr> <tr> <td>per trial mix of 0.02 m³</td> <td>8.54</td> <td>4.26</td> <td>13.58</td> <td>21.22</td> </tr> </tbody> </table>				Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg)				10 mm	20 mm	per m ³ (to nearest 5 kg)	427	213	679	1061	per trial mix of 0.02 m ³	8.54	4.26	13.58	21.22
Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg)																			
			10 mm	20 mm																			
per m ³ (to nearest 5 kg)	427	213	679	1061																			
per trial mix of 0.02 m ³	8.54	4.26	13.58	21.22																			

Items in Italic are optional limiting values that may be specified (see Section 7).
Concrete strength is expressed in the units N/mm². 1 N/mm² = 1 MN/m² = 1 MPa. (N = newton; Pa = pascal.)
The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.
SSD = based on the saturated surface-dry condition.

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Appendix 2 MATLAB code of Frequency Calculation

```

clc
clear all
%%
syms beta x E I b H A L row f k t w m J l AA BB CC DD EE;

J = m * (75/1000/2)^2 + m*L^2;

BC1 = [1 0 1 0];
BC2 = [0 1 0 1];
BC7 = [-sin(beta*L)-beta^3*J/(row*b*H)*cos(beta*L)...
-cos(beta*L)+beta^3*J/(row*b*H)*sin(beta*L)...
sinh(beta*L)-beta^3*J/(row*b*H)*cosh(beta*L)...
cosh(beta*L)-beta^3*J/(row*b*H)*sinh(beta*L)];
BC8 = [-cos(beta*L)+m*beta/(row*b*H)*sin(beta*L)...
sin(beta*L)+m*beta/(row*b*H)*cos(beta*L)...
cosh(beta*L)+m*beta/(row*b*H)*sinh(beta*L)...
sinh(beta*L)+m*beta/(row*b*H)*cosh(beta*L)];
matrix = [BC1; BC2; BC7; BC8];
sys = det(matrix);

%%
sys = matlabFunction(sys);

row = 2400;
L = 200/1000; % unit:m
b = 30/1000;
H = 25/1000;
I = b*H^3/12;
m = 720/1000;

T = 60; % temperature

E_20 = 28000*10^6;
E = E_20*(1.06-0.003*T);

s = vpasolve(sys(H,L,b,beta,m,row)==0,beta,[0.001 inf]); % beta
% s = solve(sys(H,L,b,beta,m,row)==0,beta); % beta
omega_n = s^2*((E*I)/(row*b*H))^0.5;
frequency = omega_n/(2*pi);
frequency = double(frequency)
J = m * (75/1000/2)^2 + m*L^2;

```

Appendix 3 explains the sensitivity and reliability of the used accelerometer in this study

Model	Weight gm	Sensitivity mV/g	Range g	Frequency Response Hz (±5%)	Electrical Isolation	Max. Shock gaps	Min. Temp °F (°C)	Max Temp °F (°C)	Environmental Sea	Mounting Method
3055B2	10	100	50	1 to10000	yes	2000	-60(- 51)	250(+121)	hermetic	10- 32tapped hole

