MECHANICAL PROPERTIES OF CONCRETE REINFORCED WITH STEEL FIBRE

BY

DIRISU, HENRY OGIEAKHENA
PG/ENG0003176

DEPARTMENT OF CIVIL ENGINEERIMG,
FACULTY OF ENGINEERING,
UNIVERSITY OF BENIN,
BENNIN CTY.

MARCH, 2026.

MECHANICAL PROPERTIES OF CONCRETE REINFORCED WITH STEEL FIBRE

BY

DIRISU, HENRY OGIEAKHENA
PG/ENG0003176

A PROJECT SUBMITTED TO THE DEPARTMENT OF CIVIL ENGINEERING, FACULTY OF ENGINEERING, IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF A MASTER OF ENGINEERING (M.ENG) DEGREE IN CIVIL ENGINEERING OF THE UNIVERSITY OF BENIN.

MARCH, 2026.

CERTIFICATION

This is to certify that this work was carried out by **DIRISU, HENRY OGIEAKHENA** with Matriculation Number **PG/ENG0003176**, of the Department of Civil Engineering, Faculty of Engineering, University of Benin, Benin City, Edo State Nigeria.

__________________________ _______________

Engr. Prof. S.O. Osuji **Date**
Supervisor

__________________________ _______________

Engr. Prof. Mrs. N.I. Ihimekpen **Date**
Head of Department

DEDICATION

This research work is dedicated to the Almighty God for his everlasting Faithfulness. Amen.

ACKNOWLEDGEMENTS

With profound gratitude, I acknowledge God Almighty for His unending grace, wisdom, and strength that guided me throughout the course of this academic journey.

I sincerely thank my project Supervisor, Engr. Prof. S.O. Osuji, for his patience, guidance, motivation, and extensive knowledge. His mentorship was crucial during the development of this thesis and throughout the research process. I also extend my gratitude to the Head of Department, Civil Engineering, Engr. Prof.Mrs. N.I. Ihimekpen.

I also acknowledged the expertise and guidance provided by my lecturers; Engr. Prof. O. U. Orie, Engr. Prof. R.I. Umasabor, Engr. Prof. O.R. Ogirigbo, Engr. Prof. J.O. Okovido, Engr. Prof. E.O. Nwankwo, Engr. Prof. (Mrs.) N. Kayode-Ojo, Engr. Dr. E.S. Okonofua, and Engr. Dr. U. Ukeme. Their dedication and support significantly enhanced my academic experience. Furthermore, I appreciate the invaluable assistance provided by the non-academic staff of the Department, including Mr. Frank, Secretary to the Head of Department, the laboratory technologies, and other staff of the department. Their contributions ensured the smooth operation of the department and facilitated my research. Their camaraderie and constructive feedback greatly enriched my experience and contribution to the success of this project. I am deeply grateful to my academic mentor, Engr. Dr. O. Ikhazuagbe for the knowledge he imparted to me and his genuine interest in my success in this program.

Additionally, I acknowledge my colleagues and friends who provided support and encouragement during challenging times. Finally, my heartfelt appreciation goes to my parents for their conscious prayers that have kept me going.

ABSTRACT

The problem of the increasing rate of structural failure and building collapse in Nigeria, has raised serious concerns among engineers, researchers, and regulatory bodies. This study aimed to investigate the mechanical properties of concrete reinforced with steel fibres, with particular emphasis on strength, ductility, and crack resistance.

The research involved the preparation of concrete specimens reinforced with varying proportions of steel fibres. Standard laboratory tests were conducted to evaluate key mechanical properties. Analysis was carried out on reinforced concrete with steel fibresto determine the influence of fibre inclusion on the mechanical performance of the material. The effect of curing age on compressive strength showed noticeable improvement with increased curing time.

The maximum compressive strength of 36.81 N/mm² was obtained at 28 days with 10% steel fibre content, while at 28 days, the control mix containing 0% steel fibre recorded a compressive strength of 24.44 N/mm². Similarly, the tensile strength results indicated that the highest tensile strength of 4.56 N/mm² was achieved with 10% steel fibre at 28 days, whereas the tensile strength of 3.54 N/mm² was obtained for 28 days for the mix with 0% steel fibre. For the concrete beam test results, the highest flexural strength recorded was 7.5 N/mm² for the 10% steel fibre concrete at 28 days, while the flexural strength of 6.5 N/mm² was obtained for the 0% steel fibre concrete at 28 days. These results clearly demonstrate that increasing the curing age and incorporating steel fibres as reinforcement significantly improves the mechanical properties and structural performance of concrete members.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

ACI	American Concrete Institute
FRC	Fibre-reinforced concrete
SFRC	Steel Fiber Reinforced Concrete
FHWA	Federal Highway Administration
ASTM	American Society for Testing and Materials

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Concrete is the second most consumed construction material after water with twice as much concrete used across the world than all other construction material put together Gagg (2014). Unreinforced concrete typically exhibits high compressive strength but low tensile strength. To address this limitation, steel reinforcement is used to resist tensile forces or pre-compress the concrete, enabling it to better withstand tension Jackson and Dhir, (2015). Further research is warranted to enhance the durability of concrete, given its significant benefits to society.

Steel and synthetic fibres are the two most commonly used fibre concrete in the world (Kakooei*et al*.,2012). Their mechanical properties have therefore become very important in light of the rapid transformation in their application. Various studies have covered different mix designs, fibre volumes and aspect rations but still there is a consideration gap in knowledge about the behavior of concrete reinforced with these types of fibres. Subject to the disposal and orientation of fibres in the cement matrix, the inclusion of the fibres transforms the matrix from a brittle to a ductile material (Meddah and Bencheikh, 2018). It must be well noted however that the benefit of adding fibres to concrete in construction, which is principally to improve on the residual load-bearing capacity, is influenced by the content, orientation and type of fibres in use (Mehrabi, *et al*., 2024). Fiber-Reinforced Polymer (FRP) materials are increasingly replacing conventional steel bars in certain concrete structures due to their numerous benefits, such as increased toughness, better crack resistance, and lightweight properties (Xing, *et al*., 2024).

Steel fibers have been added to concrete since the 1900s, evolving from smooth, straight fibers to modern designs with textured surfaces or shaped ends. Today, steel fiber reinforcement is a well-established method for enhancing concrete's performance, particularly in improving ductility, toughness, and strength. Its primary role is to supplement traditional reinforcement, mitigating cracking and improving resistance to impact and dynamic loads (Xing, *et al*., 2024).

1.2 Statement of the Problem

The increasing rate of structural failure and building collapse in the construction industry, particularly in developing countries such as Nigeria, has raised serious concerns among engineers, researchers, and regulatory bodies. The evidence is substantial and concrete. Over 115 building collapses occurred in Lagos alone within a decade (Okonta *et al*., 2023). Many of these failures are often attributed to poor material quality, inadequate structural design, poor workmanship, and the inherent weaknesses associated with conventional concrete. Although concrete is widely used in civil engineering construction due to its availability, durability, mouldability, and high compressive strength, it possesses relatively low tensile strength and limited resistance to cracking.

Concrete is a brittle material and is highly susceptible to the formation of cracks when subjected to tensile stresses, shrinkage, temperature variations, vibration, and repeated loading. These cracks may begin as micro-cracks and gradually propagate into visible cracks, thereby reducing the durability, service life, watertightness, and overall structural performance of concrete elements. If not properly controlled, cracking can also permit the ingress of moisture and aggressive agents, which may further deteriorate the concrete over time.

In recent years, the incorporation of steel fibres into concrete has emerged as an effective technique for improving the mechanical properties of concrete (Tadepalli, *et al., 2013)*. Steel fibres are randomly distributed discrete reinforcing elements that help to enhance tensile strength, flexural strength, impact resistance, toughness, ductility, energy absorption capacity, and crack resistance. They function by bridging micro-cracks, restricting crack growth, and improving the post-cracking behaviour of concrete under loading conditions.

Despite these advantages, the use of steel fibre reinforced concrete is still not widely adopted in many construction practices, especially in developing nations where conventional concrete remains dominant. In addition, there is still a need for more experimental data on the extent to which varying steel fibre content influences the mechanical properties of concrete, particularly with respect to compressive strength, split tensile strength, flexural strength, and durability characteristics.

Therefore, there is a need to investigate the mechanical properties of concrete reinforced with steel fibres. Understanding how steel fibres influence the behaviour and performance of concrete will contribute to the development of stronger, tougher, and more durable concrete materials. Such investigation will also provide valuable insights for engineers, designers, and construction professionals seeking innovative methods of reducing structural defects and enhancing the long-term performance of concrete structures in civil engineering applications.

1.3 Aim and Objectives of the Study

The research aimed at investigating the mechanical properties of concrete reinforced with steel fibre and steel reinforcement.

The objectives of the study are to:

i. Characterise the research materials
ii. Produce the steel fibre concrete in various proportioning
iii. Study the effect of curing age and variation in the percentage of steel fibre on the workability and compressive, tensile and flexural strength of concrete.

1.4 Justification of the Study

The increasing incidence of structural deficiencies and failures in conventional concrete structures has underscored the need for enhanced construction materials with improved performance characteristics. Although conventional concrete possesses adequate compressive strength, it offers limited resistance to crack initiation and propagation, which can adversely affect durability and long-term structural integrity.

Steel fibre–reinforced concrete (SFRC) has emerged as a promising material due to its ability to improve ductility, enhance crack control, and provide significant post-cracking strength through fibre bridging mechanisms. Despite these advantages, existing studies present inconsistent findings regarding the influence of steel fibres on key mechanical properties such as compressive strength, tensile strength, flexural strength, and shear resistance, particularly at varying fibre volume fractions.

Furthermore, practical challenges associated with the use of steel fibres—including reduced workability, increased material cost, potential durability concerns, and difficulties in mixing and placement—have not been comprehensively addressed in many studies. These gaps limit the reliable application of SFRC in structural engineering practice.

This study is therefore justified as it seeks to systematically evaluate the mechanical behaviour of concrete reinforced with steel fibres. The research aims to generate experimental data that will contribute to a clearer understanding of steel fibre reinforcement, thereby supporting safer, more economical, durable, and performance-based concrete design.

1.5 Scope of the Study

The scope of the study includes:

i. Characterization of materials, various tests were conducted, such as grain size analysis, density measurements, specific gravity, and aggregate strength assessments (crushing and impact values), providing essential data for material evaluation.

ii. A concrete mix with a ratio of 1:1½:3 (cement: sand: granite) were prepared using a water-cement ratio of 0.55 for cubes casting, cylinders, and beams.

iii. Experimentally investigates the structural properties of concrete with steel fibers and steel reinforcement at both fresh and hardened stages. Tests were conducted on normal concrete cubes and cylinders at curing ages of 7, 14, 21, and 28 days, evaluating properties such as slump value, setting time, workability, curing rate, compressive strength, tensile strength, and flexural strength.

The study was limited to granite having water cement ratio of 0:55, and a mix ratio of 1:1.5:3. The percentage of steel fibres used in this study was 0% to 10%. The study also focuses on specific properties of concrete, including sieve analysis, slump test, and density, moisture content and mechanical strengths (compressive, tensile, and flexural).

CHAPTER TWO

LITERATURE REVIEW

2.1 Concrete

Concrete is the second most consumed construction material in the world after water, with approximately twice as much concrete used globally than all other construction materials combined (Woodward and Duffy, 2011). Its pre-eminence as the dominant structural material of the modern era is underscored by the scale of its production: global concrete consumption now exceeds 30 billion tonnes annually, sustained by the production of more than 4 billion tonnes of cement each year (Mehta and Monteiro, 2014). These figures reflect the material's unrivalled combination of relative low cost, ready availability of raw constituents, adaptability to diverse structural applications, and inherent durability. From residential housing and road pavements to large-scale infrastructure such as dams, bridges, and offshore platforms, concrete remains indispensable to civil engineering practice.

Concrete is a composite material formed by combining a binding medium — typically Portland cement paste — with coarse and fine aggregates and sufficient water to initiate the chemical reaction known as hydration (Neville, 2011). A critical limitation of plain concrete as a structural material is its characteristically low tensile strength relative to its compressive capacity. The tensile strength of concrete is only approximately 7 to 15 percent of its compressive strength, and the material can therefore be classified as quasi-brittle (Bazant *et al*., 1993; An *et al*., 2020). This disparity arises from the presence of inherent micro-cracks and air voids that form during casting, mixing, and the curing process, stress concentrations at these discontinuities causing the initiation and rapid propagation of fracture under tensile loading (An *et al*., 2020). Durability is the ability of concrete to resist deterioration under the environmental and mechanical actions to which it is subjected during its service life, and it is now recognised as equally important as structural strength in the design of concrete structures (Neville, 2011). The durability of concrete is intrinsically linked to the permeability of the hardened cement paste: a dense, low-permeability microstructure reduces the ingress of water, chloride ions, carbon dioxide, and sulfates, all of which can initiate chemical deterioration or corrosion of embedded steel (Mehta and Monteiro, 2014).

In summary, concrete is a versatile, cost-effective, and globally dominant construction material whose performance in compression far exceeds its performance in tension. Its constituent materials, proportioning, and production processes are well understood, yet its inherent brittleness and low tensile capacity impose significant limitations on its use as a standalone structural material. These limitations have driven the development of reinforced concrete systems in which steel reinforcement bars and, more recently, discontinuous fibre reinforcements are incorporated to compensate for the tensile deficiency.

2.2 Properties of Conventional Concrete

Conventional concrete- also referred to in practice as normal-strength or ordinary Portland cement concrete- is defined for the purposes of this review as concrete with a 28-day characteristic compressive cylinder strength in the range of approximately 20 MPa to 55 MPa, produced from standard Portland cement, natural fine and coarse aggregates, and water, with or without conventional chemical admixtures (Mehta and Monteiro, 2014; Kosmatka and Wilson, 2016). The structural and serviceability performance of any reinforced concrete element is governed not only by the compressive strength of the concrete but by the full suite of its mechanical, deformation, and physical properties. These include tensile and flexural strength, modulus of elasticity, Poisson's ratio, creep, drying shrinkage, and thermal behaviour. A thorough understanding of each of these properties, their typical magnitudes, and the factors governing their variation is essential to the rational design of concrete structures and forms the necessary precursor to evaluating the enhancements achievable through steel fibre.

2.2.1 Compressive Strength

Compressive strength is the most fundamental mechanical property of concrete and serves as the primary index on which mix design, structural design, and quality control are based (Neville, 2011). It is measured on standard 150 mm cubes or 150 × 300 mm cylinders cured for 28 days under standard conditions, with cylinder strengths typically 0.8 times the corresponding cube strengths. For conventional normal-strength concrete, characteristic compressive strengths of 20 MPa to 40 MPa are most commonly specified, though structural applications may extend this range to 55 MPa without recourse to the special mix constituents associated with high-strength or high-performance concrete (Mehta & Monteiro, 2014). Compressive strength is principally governed by the water-to-cement (w/c) ratio, the cement type and content, the nature and grading of aggregates, the degree of compaction, and the curing regime applied after casting (Neville, 2011). At a constant w/c ratio, strength increases with cement content up to a limiting value beyond which excess cement introduces heat-of-hydration cracking without proportionate strength gain. The relationship between w/c ratio and compressive strength is non-linear, and a reduction in w/c ratio from 0.65 to 0.45 can typically double the 28-day compressive strength of a mix (Mehta & Monteiro, 2014).

2.2.2 Tensile Strength

The tensile strength of conventional concrete is substantially lower than its compressive strength, typically falling in the range of 2 MPa to 5 MPa and representing only 7 to 15 percent of the compressive strength value (Neville, 2011). This pronounced asymmetry between compressive and tensile capacities arises from the presence of pre-existing micro-cracks and pores within the hardened cement paste matrix, which act as stress concentrators under tensile loading and promote brittle fracture at relatively low applied stresses (Bažant and Planas, 1998). Two standardised test methods are widely employed to characterise the tensile capacity of concrete: the splitting tensile test (ASTM C496), in which a cylinder is loaded diametrically in compression to induce indirect tension, yielding a splitting tensile strength of approximately 10 percent of compressive strength; and the modulus of rupture test (ASTM C78), which measures flexural or bending tensile strength by loading a beam in third-point bending (FHWA, 2012). Flexural strength, or modulus of rupture, is somewhat higher than the direct tensile strength, typically ranging from 3 MPa to 5 MPa for normal-strength mixes, and is empirically related to compressive strength by the expression $f_r = 0.62\sqrt{f'c}$ (MPa) as specified by ACI 318 (American Concrete Institute [ACI], 2019). The inherent weakness of plain concrete in tension underpins the primary structural limitation of the material and represents the principal motivation for reinforcement.

2.2.3 Modulus of elasticity

The modulus of elasticity, or Young's modulus, of concrete is a measure of its stiffness and is defined as the ratio of stress to strain within the elastic range of behaviour. For conventional concrete, the static secant modulus of elasticity typically lies in the range of 14 GPa to 41 GPa, with values for normal-density concrete of compressive strength 20 MPa to 40 MPa most commonly falling between 20 GPa and 30 GPa (Engineering Toolbox, 2023). The modulus of elasticity is not a fixed material constant but varies with compressive strength, aggregate type, density, age, and moisture condition (Noguchi *et al*., 2009). The most widely used empirical relationship, adopted by ACI 318, expresses the modulus as Ec = 4700√f'c (MPa), a formula derived from extensive experimental datasets on normal-weight concrete (ACI, 2019). The modulus of elasticity governs the deflection of concrete structural members under service loads and the distribution of stresses in statically indeterminate structures; consequently, its accurate determination is critical to serviceability limit state design.

2.2.4 Poisson's ratio

Poisson's ratio for conventional concrete, defined as the ratio of lateral strain to longitudinal strain under uniaxial compressive loading within the elastic range, is relatively consistent across mix types, typically ranging from 0.15 to 0.22, with a commonly adopted design value of 0.20 (Neville, 2011; Engineering Toolbox, 2023). This parameter is of particular relevance in three-dimensional stress analyses and finite element modelling of concrete structures, where the multiaxial stress state must be fully characterised. Poisson's ratio remains approximately constant at stress levels below about 70 percent of the compressive strength, beyond which microcracking causes a marked increase in lateral strain and an apparent rise in the measured ratio as the material approaches failure (Neville, 2011).

2.2.5 Creep

Creep is the time-dependent increase in strain that occurs in concrete subjected to a sustained load at constant stress, and it represents one of the most practically significant deformation properties of the material (Neville, 2011). Under sustained compressive loading, concrete exhibits time-dependent deformation (creep), whereby strain continues to increase long after the initial elastic response. This delayed deformation can significantly exceed the instantaneous strain, often reaching multiples of the initial elastic deformation in normal-strength concrete. (Hong, 2023; Usibe, 2025). Creep originates in the viscous flow of the C-S-H gel within the hardened cement paste and in the movement of adsorbed water within the gel pores under stress. The magnitude of creep in concrete is governed by several interrelated factors, including the level of sustained stress relative to strength, water–cement ratio, age at loading, ambient relative humidity, cement content, and aggregate volume fraction. These parameters influence the viscoelastic behaviour of concrete by affecting its microstructure, moisture movement, and stiffness, thereby controlling the extent and rate of time-dependent deformation (Hong, *et al*., 2023; ACI Committee 209, 2023).

2.2.5 Shrinkage

Drying shrinkage in concrete refers to the reduction in volume that occurs as moisture is lost to the surrounding environment through evaporation, and it is distinct from autogenous shrinkage, which arises from internal self-desiccation during cement hydration. The magnitude of drying shrinkage in conventional concrete typically falls within the range of 400 to 800 microstrain ($\times 10^{-6}$), depending on factors such as mix composition, curing conditions, and environmental exposure. In reinforced concrete elements, however, the effective shrinkage strain is generally reduced to about 200 to 300 microstrain due to the restraining effect of embedded steel reinforcement, which limits free deformation (Neville and Brooks, 2021; ACI Committee 209, 2023). Unrestrained shrinkage does not induce stresses, but when shrinkage is restrained by boundary conditions, other structural elements, or embedded reinforcement, tensile stresses develop within the concrete. Where these tensile stresses exceed the low tensile strength of plain concrete, cracking occurs, compromising both the structural integrity and the durability of the element by providing pathways for the ingress of harmful agents (Mehta and Monteiro, 2014). The principal factors influencing drying shrinkage include the water content of the mix, the cement content, the aggregate volume and stiffness, the size and shape of the member, the ambient relative humidity, and the duration of curing (Neville, 2011).

2.2.6 Thermal properties

The thermal properties of conventional concrete are of practical significance in the design of structures subject to thermal loading, fire, or significant daily and seasonal temperature variation. The coefficient of thermal expansion of normal-weight concrete typically ranges from 7 to 12×10^{-6} per °C, with a widely used design value of approximately 10×10^{-6} per °C, dependent primarily on the type of coarse aggregate (Neville, 2011; Engineering Toolbox, 2023). The thermal conductivity of conventional concrete typically ranges between 0.8 and 1.4 W/m·K, while its specific heat capacity is generally in the range of 0.75 to 1.00 kJ/kg·K. These thermal properties give concrete a moderate thermal mass, enabling it to absorb, store, and gradually release heat, which is beneficial in passive solar building design and enhancing indoor thermal stability (Subedi, *et al*., 2025; ACI Committee 122, 2022). Concrete generally exhibits satisfactory performance under fire exposure compared to steel, as it is non-combustible and retains a substantial proportion of its compressive strength at elevated temperatures, though spalling can occur in high-strength concrete at temperatures above approximately 300°C (Neville, 2011).

These properties of conventional concrete present a characteristic profile of strengths and limitations. Its compressive strength is well understood, reliably controllable through mix design, and sufficient for the majority of structural applications. However, its tensile and flexural strengths are low relative to compressive strength, its stiffness is moderate compared to steel, and its time-dependent deformations — creep and shrinkage — impose significant challenges in serviceability design. Most critically, the brittleness of plain concrete and its limited tensile capacity render it structurally inadequate when subjected to bending, shear, or impact forces without supplementary reinforcement. These inherent deficiencies collectively define the rationale for the use of steel fibre reinforcement in concrete construction, as reviewed in the sections that follow.

2.3 Steel Fibre

Steel fibres are short, discrete lengths of steel, typically with aspect ratios (length-to-diameter) ranging from about 20 to 100, which are uniformly dispersed within the concrete matrix to act as micro-reinforcement. Their primary function is to bridge cracks, improve post-cracking behaviour, enhance tensile and flexural strength, and increase the toughness and energy absorption capacity of concrete. Unlike conventional reinforcing bars, steel fibres are randomly distributed throughout the concrete, enabling more effective control of micro-cracking and contributing to improved durability and impact resistance (ASTM, 2020; fib, 2013; ACI, 2018).

Steel fibres are the most commonly used fibres in concrete due to their superior mechanical performance. They are particularly effective in improving toughness, ductility, fatigue resistance, and crack control. Their use enhances post-cracking behaviour, making them suitable for structural and pavement applications where resistance to dynamic and impact loading is critical (ACI, 2018; Neville, 2011).

Steel fibres are among the most widely used types of fibre reinforcement in concrete. Although initially introduced to mitigate plastic shrinkage cracking, recent studies have demonstrated that steel fibres significantly improve flexural strength, toughness, ductility, and crack resistance. They also enhance durability by reducing permeability and controlling crack widths. These improvements have been consistently observed across various experimental investigations and reviews of steel fibre-reinforced concrete (SFRC) (Ramazani *et al*., 2024; Zheng *et al*., 2024).

2.3.1 Types and Geometry of Steel Fibres

Steel fibres used in concrete composites can broadly be classified as deformed or un-deformed (straight) based on their geometry. Commercially, straight steel fibres are uncommon in modern practice, as virtually all available fibres are manufactured with a mechanically pre-deformed profile to enhance bonding with the cementitious matrix (Mujalli *et al*., 2022). Deformation may occur at the fibre ends — as in the case of hooked, paddled, or button-end fibres — or along the entire length of the fibre, as observed in crimped, indented, twisted, and corrugated forms. The principal reason for mechanically deforming fibres is to generate mechanical anchorage within the matrix, which significantly increases pull-out resistance and, consequently, the energy absorption capacity of the composite.

Among the available types, hooked-end steel fibres are the most extensively used in structural applications. Due to the presence of mechanically deformed hooks at both ends, these fibres develop strong pull-out resistance through mechanical interlocking within the concrete matrix, thereby generating a higher bond strength than straight or crimped fibres (Vijayan *et al*., 2022). Niu *et al*. (2023) confirmed that the best flexural performance in SFRC is generally produced by hooked-end fibres, attributed to their superior interfacial bond behaviour. Similarly, crimped or wavy fibres derive their bonding mechanism from distributed frictional resistance along their corrugated length, while straight fibres rely primarily on frictional bond, which is comparatively lower. Twisted fibres, on the other hand, exhibit exceptional tensile strength and are increasingly employed in Ultra-High Performance Concrete (UHPC) matrices.

Beyond shape, fibres are characterised by their aspect ratio, defined as the ratio of fibre length to fibre diameter (l/d). This parameter is among the most critical in governing the mechanical performance of SFRC. Typical commercial steel fibres have aspect ratios ranging from 30 to 150, with values around 60–80 generally recognised as optimal for balancing mechanical improvement and workability (Yang *et al*., 2024; Gong *et al*., 2023). An increase in aspect ratio generally enhances the post-cracking performance by improving the fibre-matrix interfacial contact area, but excessively high aspect ratios can cause fibre balling during mixing, reducing workability and leading to non-uniform distribution within the matrix.

Figure 2.1 illustrates the engineering characteristics of steel fibres and their shape, which are critical parameters influencing the overall behaviour of SFRC.

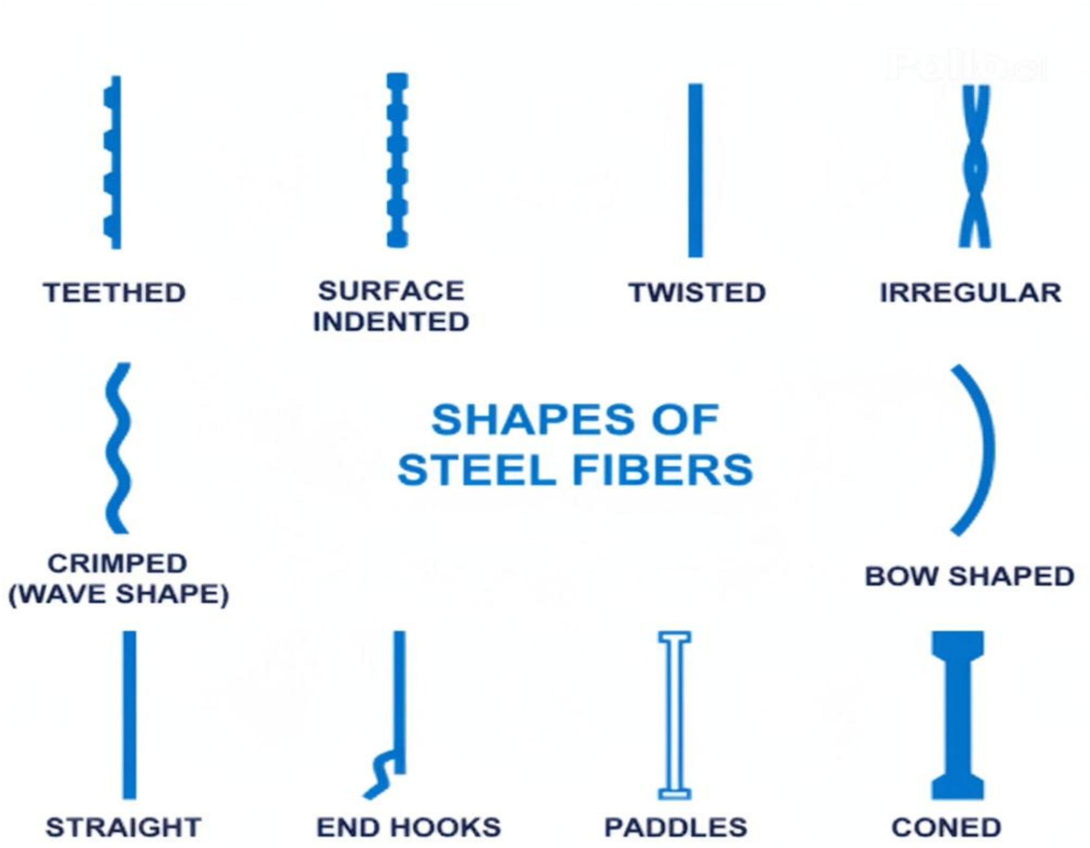

Figure 2.1:Different shapes of steel fibres (Sources: Vijayan *et al*, 2022)

2.4 Fibre-Reinforced Concrete (FRC):

The development of fibre-reinforced concrete (FRC) began with early experimental studies by Romualdi, and Batson (1963), which demonstrated the effectiveness of closely spaced fibres in controlling crack propagation. Subsequent advancements have led to the widespread application of fibre reinforcement in concrete technology. Fibres incorporated into concrete are effective in controlling plastic and drying shrinkage, thereby reducing early-age cracking. They also enhance flexural toughness, energy absorption capacity, and ductility, contributing significantly to improved durability and post-cracking performance of concrete. These improvements are primarily attributed to the crack-bridging mechanism of fibres, which delays crack propagation and enhances residual strength (Zhang *et al*., 2025; Koo *et al*., 2023).

Fibre-reinforced concrete (FRC) is a composite material consisting of a cementitious matrix reinforced with short, discrete fibres that are randomly distributed throughout the mix. These fibres act as internal reinforcement, improving the mechanical behaviour of concrete, particularly under tensile and flexural loading conditions (Mohamed *et al*., 2024).

Fibres used in cement-based composites can be manufactured from steel, glass, synthetic polymers, or natural materials. Due to their relatively uniform distribution and close spacing within the matrix, fibres effectively control crack initiation and propagation at both micro- and macro-levels. However, fibres are not intended to replace conventional steel reinforcement bars; rather, they serve a complementary role. While steel bars provide primary structural capacity, fibres enhance crack control, toughness, and resistance to impact and fatigue loading. The combined use of both systems can significantly improve structural performance (Shiferaw and Kanakubo, 2025).

2.4.1 Steel Fiber Reinforced Concrete (SFRC)

The use of fibrous reinforcement in brittle construction materials is not a modern concept; the practice dates to antiquity when straw and horsehair were added to mud bricks. The development of steel fibres as a modern reinforcing element for concrete, however, began in the early 1960s (Mujalli *et al*., 2022). Since then, research and industrial practice have expanded tremendously, and SFRC has become one of the most widely used and rapidly growing fibre-reinforced composite materials in civil engineering. It is today employed in a diverse range of structural and non-structural applications, including industrial floor slabs, tunnel linings, pavements, precast elements, hydraulic structures, and seismic-resistant systems (Niu *et al*., 2023; Vijayan *et al*., 2022).

Steel Fibre Reinforced Concrete (SFRC) is a composite construction material consisting of a conventional hydraulic cement concrete matrix into which short, discrete, and randomly distributed steel fibres are uniformly incorporated. The primary purpose of these fibres is to arrest crack initiation and propagation, thereby transforming concrete from a brittle material into one capable of exhibiting substantial post-cracking ductility and energy absorption. According to Mujalli *et al*. (2022), the key role of steel fibres in the concrete matrix is to aid in mitigating the propagation of micro cracks, whereby the fibres bridge the crack surfaces and restrain the growth of macro-cracks, significantly enhancing the tensile toughness and residual strength of the material.

SFRC is defined by the inclusion of discontinuous steel fibres within the concrete matrix, which act as crack arrestors by bridging microcracks and delaying crack propagation. This mechanism enhances key mechanical properties such as toughness, tensile strength, and energy absorption capacity, making SFRC suitable for structural and pavement applications subjected to dynamic and impact loading. (Ren, 2024). The performance of SFRC is influenced by several parameters, including fibre aspect ratio (length-to-diameter ratio), fibre volume fraction, geometry, and distribution within the mix. Typical aspect ratios for steel fibres range between approximately 20 and 100, depending on the application and desired performance characteristics. (Ren, 2024).

However, the inclusion of steel fibres tends to reduce the workability of fresh concrete due to increased internal friction and fibre interlocking. To mitigate this effect and ensure proper mixing, placement, and compaction, chemical admixtures such as superplasticizers are commonly incorporated into SFRC mixtures.

The behavior of SFRC can be classified into three groups according to its application, fiber volume percentage and fiber effectiveness; for instance, SFRC is classified based on its fiber volume percentage as follows:

i. Very low volume fraction of SF (less than 1% per volume of concrete), which has been used for many years to control plastic shrinkage and as pavement reinforcement.
ii. Moderate volume fraction of SFs (1% to 2% per volume of concrete) which can improve modulus of rupture (MOR), flexural toughness, impact resistance and other desirable mechanical properties of concrete.
iii. High volume fraction of SFs (more than 2% per volume of concrete) used for special applications such as impact and blast resistance structure; these include SIFCON (Slurry Infiltrated Fiber Concrete), SIMCON (Slurry Infiltrated Mat Concrete).

2.4.2 Fibre - Matrix Interfacial Bond Behaviour

The mechanical performance of SFRC is fundamentally governed by the bond behaviour at the interface between the steel fibre and the cementitious matrix. The bonding mechanisms in SFRC are complex, involving the combined action of chemical adhesion, friction, and mechanical anchorage arising from the geometric deformation of fibres (Mujalli *et al*., 2022). In straight fibres, the frictional component of bond predominantly controls the pull-out behaviour, whereas in deformed fibres - such as hooked-end and crimped configurations -

the mechanical anchorage component is the dominant force-transfer mechanism. Consequently, researchers have consistently recommended the use of deformed steel fibres to improve bond behaviour (Mujalli *et al*., 2022).

When the concrete matrix cracks under loading, the fibres bridging the crack surfaces resist further crack opening by transferring tensile stresses across the crack plane. This mechanism, commonly referred to as crack bridging, is the primary mode through which steel fibres enhance the post-cracking strength and ductility of concrete (Niu *et al*., 2023). The effectiveness of this bridging action depends on the orientation of fibres relative to the crack plane, the embedded length of the fibres, the anchorage strength, and the tensile capacity of the fibre itself. Fibres that fracture before being pulled out from the matrix do not contribute to energy absorption beyond their fracture load; hence, it is more desirable for fibres to pull out gradually, as this dissipates considerably more energy (Mujalli *et al*., 2022). The Interfacial Transition Zone (ITZ) between the fibre surface and the surrounding paste is particularly important, as its microstructural quality directly affects the bond efficiency.

2.5 Influence of Steel Fibre on the Mechanical Properties of SFRC

The incorporation of steel fibres into conventionally reinforced concrete has been shown to significantly enhance its mechanical performance. Steel fibres improve tensile and flexural strength, increase ductility, and enhance post-cracking behaviour by bridging cracks and transferring stresses across them. This results in improved toughness, energy absorption capacity, and resistance to crack propagation. Additionally, steel fibres contribute to better shear performance and impact resistance, while also reducing crack widths and spacing, thereby complementing the action of conventional reinforcing bars.

2.5.1 Influence of Steel Fibres on Compressive Strength

The influence of steel fibre inclusion on the compressive strength of concrete is generally modest compared to the improvements recorded in tensile and flexural properties. Numerous experimental studies have reported that the addition of steel fibres can increase compressive strength in the range of approximately 4–25%, depending on fibre volume fraction, aspect ratio, fibre geometry, and the strength class of the base concrete (Yang *et al*., 2024). This improvement is primarily attributed to the confinement effect exerted by the randomly distributed fibres within the matrix, which impedes the lateral dilation of concrete specimens under axial compression and delays the coalescence of internal microcracks.

Gong *et al*. (2023) observed that the compressive strength of SFRC generally increases with increasing fibre volume fraction, but only up to an optimum threshold. Beyond this threshold - typically in the range of 1.0 –1.5% by volume: workability deteriorates due to fibre clustering and entrapped air voids, which can offset the strength gains and may even reduce compressive strength. Yang *et al*. (2024) further reported that the aspect ratio of steel fibres exerts a significant influence on compressive behaviour: fibres with higher aspect ratios improved compressive strength more effectively at moderate volume fractions, whereas at high volume fractions, fibres with excessively large aspect ratios led to workability issues that diminished performance. Importantly, the compressive strength of SFRC improves more noticeably in lower-strength concrete matrices, where fibre confinement has a greater relative impact.

2.5.2 Influence on Tensile and Flexural Strength

The most significant contributions of steel fibres to concrete performance are recorded in tensile and flexural strength. Plain concrete is characteristically brittle in tension, with flexural strength typically falling within 10–15% of its compressive strength (Karzad *et al*., 2023). The incorporation of steel fibres substantially enhances both the pre-cracking and post-cracking tensile capacity of the composite. The fibres prevent cracks from forming and spreading freely, and through their bridging effect, they maintain residual tensile strength well beyond the point of first cracking. Karzad *et al*. (2023) demonstrated through experimental flexural testing of SFRC prisms with varying fibre volume fractions (1%, 1.5%, and 2%) and concrete compressive strengths (40–70 MPa) that increasing fibre content consistently enhanced both peak flexural strength and post-peak ductility.

The flexural behaviour of SFRC depends on a multitude of interacting factors, including the matrix compressive strength, fibre material properties, fibre geometry, fibre volume fraction, and the nature of the fibre–matrix interface (Niu *et al*., 2023). Niu *et al*. (2023) evaluated five distinct steel fibre types — milled, corrugated, and hooked-end fibres of varying aspect ratios (45, 55, and 65) — and found that hooked-end fibres with higher aspect ratios consistently produced superior flexural strength and post-peak ductility. This finding aligns with the work of Gong *et al*. (2023), who reported that both single and hybrid steel fibre configurations improve crack deformation resistance and tensile properties, with hybrid steel fibres exhibiting a more significant overall improvement, and with volume fractions above 0.6% producing a clearly defined post-peak descending response indicative of energy absorption capability.

In terms of splitting tensile strength, research has demonstrated improvements ranging from 20% to over 80% compared to plain concrete, depending on fibre type and dosage. Yang *et al*. (2024) noted that as the fibre volume fraction increased from 0% to 1.5%, the split tensile strength of SFRC rose substantially; however, a marginal decrease was observed at volume fractions above 1.5–2%, attributed to fibre clustering effects. The residual flexural strength parameters - fR1, fR2, fR3, and fR4 — as defined by EN 14651 have been extensively used in recent literature to characterise the post-cracking performance of SFRC at serviceability and ultimate limit states. García-Taengua *et al*. (2021) established through multivariate regression analysis of a large SFRC database that these parameters are governed primarily by the fibre content, fibre aspect ratio, and fibre tensile strength, with concrete compressive strength playing a secondary but important role.

2.5.3 Toughness and Energy Absorption Capacity

Toughness, defined as the ability of a material to absorb energy up to fracture, is substantially improved in SFRC relative to plain concrete. This property is quantified through the area under the load-deflection or stress-crack mouth opening displacement (CMOD) curve obtained from standard flexural tests, such as those prescribed by ASTM C1609 and EN 14651. The fibres contribute to toughness through three synergistic mechanisms: (i) prevention of crack initiation by resisting stress concentrations at micro crack tips; (ii) crack bridging that increases the post-peak load-carrying capacity; and (iii) the pull-out energy dissipated as fibres are progressively extracted from the matrix as cracks widen (Niu *et al*., 2023).

A review of the fracture properties of SFRC by Xie *et al*. (2023) concluded that fracture toughness increases significantly with the increase of randomly distributed steel fibre volume fraction from 0 to 1.6%. The same review identified that aligned steel fibre reinforced concrete exhibits fracture properties approximately 1.3–1.79 times higher than those of randomly distributed SFRC, highlighting the importance of fibre orientation relative to the principal tensile stress direction. The toughness indices defined under ASTM C1018-which relate post-cracking absorbed energy to first-crack energy — have been consistently reported to improve with fibre dosage, with researchers noting up to threefold improvements in toughness at volume fractions of 1.5–2% (Vijayan *et al*., 2022).

2.5.4 Shear Strength Enhancement

The addition of steel fibres to concrete is particularly effective in improving shear resistance, a property of critical structural significance. In conventional reinforced concrete, shear capacity is often the governing design criterion for slender beams without adequate transverse reinforcement. Steel fibres can partially or fully substitute for conventional shear stirrups, as the randomly oriented fibres bridging diagonal shear cracks effectively resist crack propagation and transfer tensile stresses across the crack plane. Yang *et al*. (2024) reported that in reinforced slender beams, adding fibres at a volume fraction of 1% resulted in a shear capacity 128% higher than that of an equivalent plain concrete beam without stirrups, demonstrating the extraordinary potential of SFRC in shear-critical applications.

Vijayan *et al*. (2022) confirmed this finding through a comprehensive review of SFRC in structural applications, reporting that steel fibres consistently enhance both the shear capacity and the post-cracking shear ductility of beams and slabs. The fibres act as distributed shear reinforcement, not only increasing the peak shear load but also improving the post-failure energy absorption capacity of the structural element. At the material level, the randomly distributed fibres inhibit the propagation of diagonal tension cracks by introducing additional crack-plane shear transfer mechanisms, analogous in principle to aggregate interlock but operative at a larger scale. Several design codes — including RILEM TC 162-TDF, fib Model Code 2010, and ACI 544- now provide methods for calculating the shear contribution of steel fibres in SFRC structural members.

2.5.5 Impact and Dynamic Load Resistance

The impact resistance of SFRC is markedly superior to that of plain concrete, making it an attractive material for structures subjected to dynamic loading, blast effects, or repeated impact actions. Impact resistance encompasses both the energy required to initiate the first crack and the total energy absorbed until failure, with steel fibres being particularly effective at improving the latter. Xie *et al*. (2023) reviewed experimental evidence showing that steel fibre content of no more than 1.0% by volume can substantially improve impact resistance, attributing this enhancement to the fibres' inhibiting effect on micro crack propagation, which delays the transition from stable micro crack growth to unstable macrocrack failure during impact loading.

Drop-weight impact tests conducted in numerous studies have demonstrated that SFRC specimens sustain significantly more blows before first cracking and final failure compared to equivalent plain concrete specimens. Vijayan *et al*. (2022) cited experimental evidence showing that high-strength SFRC with hooked-end fibres achieved initial cracking and failure strengths approximately 3.9 and 4.2 times greater, respectively, than those of equivalent high-strength concrete without fibres. Furthermore, strain rate hardening effects have been observed in SFRC under dynamic loading conditions, confirming that the mechanical performance of the material under impact is superior to that recorded under quasi-static loading. This behaviour makes SFRC particularly suitable for military infrastructure, blast-resistant structures, industrial flooring under heavy machinery, and tunnel linings in areas subject to dynamic ground movement.

2.5.6 Durability and crack width control

The durability of concrete structures is intimately related to crack control, as cracks provide pathways for the ingress of aggressive agents- including chlorides, sulphates, and carbon dioxide - that accelerates corrosion of embedded steel reinforcement and deterioration of the concrete matrix. SFRC offers a significant advantage in this regard, as the fibres bridge early-age cracks (including plastic shrinkage cracks) and limit crack widths under service loading, thereby reducing permeability and enhancing resistance to chemical attack (Yang *et al*., 2024). A state-of-the-art review by Fibre-Reinforced Concrete: State-of-the-Art-Review on Bridging Mechanism, Mechanical Properties, Durability, and Eco-economic Analysis (Pham, 2025) identified that micro fibres are generally more effective than macro fibres in reducing permeability and chloride diffusion, while longer, deformed fibres contribute more to macro-crack control.

At elevated temperatures - a condition relevant to both fire exposure and industrial applications -SFRC demonstrates improved residual mechanical performance compared to plain concrete. Liu *et al*. (2024) investigated the mechanical properties of steel fibre-reinforced rubber concrete after exposure to temperatures ranging from 20 to 800°C, confirming that steel fibres reduce the risk of spalling and inhibit crack extension, thereby enhancing the post-fire residual compressive, tensile, and flexural strength of the specimens. The study found that at high steel fibre dosages (1.2% by volume), the mechanical degradation due to elevated temperatures was substantially moderated. In addition, SFRC exhibits superior resistance to freeze-thaw cycling compared to plain concrete, since the restriction of crack growth by fibres reduces the rate of internal damage accumulation under cyclic thermal loading.

2.6. Key Factors Governing SFRC Performance

The mechanical performance of SFRC is governed by a complex interplay of material and geometric parameters. The principal factors identified in recent literature include:

(i) fibre volume fraction (Vf), which directly determines the density of crack-bridging fibres across any given crack plane;

(ii) aspect ratio (l/d), which governs the bond and pull-out response;

(iii) fibre shape and surface geometry, which control the mechanism and magnitude of bond;

(iv) the compressive strength of the base concrete matrix, which influences the fibre–matrix ITZ quality and the fracture toughness of the matrix; and

(v) fibre distribution and orientation, which determine the effective reinforcing efficiency of the fibre dosage (Yang *et al*., 2024; García-Taengua *et al*., 2021).

Workability is an additional practical consideration of considerable importance. The introduction of steel fibres generally reduces the slump and flowability of fresh concrete, with the effect becoming more pronounced at higher volume fractions and higher aspect ratios. Experimental results reported by Yang *et al*. (2024) indicated that adding 0.5–1.5% by volume of steel fibres can reduce concrete slump by 65–90 mm. Admixtures such as superplasticisers and pozzolanic additions (silica fume, fly ash) are frequently employed in SFRC mix designs to recover workability without compromising the water-to-cement ratio, thereby maintaining or improving the long-term mechanical and durability properties of the hardened composite. The optimisation of SFRC mix design - balancing fibre content, matrix quality, and workability - remains an active area of research, with recent computational and statistical modelling tools increasingly employed to identify optimal combinations for specific structural performance targets (García-Taengua *et al*., 2021; Karzad *et al*., 2023).

2.8 Applications of SFRC in Structural Engineering

The unique combination of enhanced toughness, crack control, tensile and shear strength, and impact resistance has led to the widespread adoption of SFRC in a broad spectrum of structural engineering applications. Industrial floor slabs represent one of the most significant current uses of SFRC, where the material's high toughness and resistance to punching and impact loads under forklift and heavy machinery traffic are particularly valued. In tunnel engineering, SFRC has established itself as a standard segment material for shield-driven tunnels, replacing or supplementing conventional rebar cages with steel fibre reinforcement to achieve thinner, lighter, and more durable precast segments (Yang *et al*., 2024).

In structural members, the incorporation of steel fibres in beams has been demonstrated to substantially reduce the required quantity of conventional shear stirrups, leading to improvements in constructability and reductions in reinforcement congestion. Vijayan *et al*.

(2022) reported that steel fibres enhance the seismic performance of shear walls, improving ductility, reducing reinforcement congestion, and enhancing post-peak load-carrying capacity under cyclic loading. For bridge deck slabs and pavements, SFRC offers excellent resistance to fatigue loading, thermal cracking, and impact from traffic, making it a durable and cost-effective alternative to conventional reinforced concrete. The material has also found increasing application in blast-resistant and protective structures, where its capacity to absorb energy from explosive loading and resist progressive collapse is a critical asset (Vijayan *et al*., 2022).

More recently, research has explored the hybrid use of steel fibres combined with conventional steel reinforcing bars (reinforcement bars) in structural elements, recognising that each reinforcement type operates at a different scale of crack development and contributes complementarily to structural behaviour. The fibres control micro crack initiation and propagation, improving the serviceability performance and tensile toughness of the matrix, while the reinforcement bars provide the primary resistance to large-deformation yielding and ultimate load capacity.

2.9 Review of Related Previous Studies

A substantial body of experimental and analytical literature exists on the behaviour of steel fibre-reinforced concrete (SFRC), spanning more than six decades of research. The reviewed studies encompass a broad range of investigations into the mechanical properties, flexural and shear behaviour, ductility, toughness, crack control, of con concrete reinforced with steel fibres. The present section synthesises the findings of eighteen directly relevant studies, arranged in approximate chronological order, to establish the research landscape within which the current experimental programme is situated. Table 2.1 subsequently presents a structured summary of the reviewed literature.

1. Romualdi and Batson (1963) - Mechanics of Crack Arrest in Concrete

Romualdi and Batson (1963) are widely credited with providing the earliest systematic theoretical and experimental investigation into the mechanics of crack arrest in concrete by means of closely-spaced wire reinforcement. The study proposed that the tensile strength of fibre-reinforced concrete was governed by the spacing between wire elements relative to the stress intensity at the crack tip. As wire spacing decreased, the crack tip stress intensity was reduced, thereby requiring greater applied load to initiate crack propagation. Beams and cylinders reinforced with fine-wire reinforcement at defined spacings were tested in direct tension and flexure.

The results demonstrated that closely-spaced wire reinforcement significantly increased the apparent tensile strength of the matrix and substantially delayed crack initiation and propagation. The study established the theoretical underpinning for SFRC technology, revealing that the effectiveness of fibre reinforcement depended critically on fibre spacing and the associated stress intensity factor rather than on the total volume of fibres alone. This foundational contribution informed subsequent decades of fibre-reinforced concrete research and led directly to the development of standardised discrete fibre systems for practical application.

2. Khaloo and Kim (1997) - Shear behaviour of SFRC Under Direct Shear

Khaloo and Kim (1997) examined the influence of concrete matrix strength and fibre characteristics on the behaviour of SFRC under direct shear using Z-type push-off specimens. The investigation encompassed normal- and high-strength concrete matrices reinforced with hooked-end steel fibres at varying dosages. The study systematically assessed the relative contributions of the concrete matrix strength and fibre reinforcement index to ultimate shear capacity.

The findings indicated that steel fibres with a dosage of up to 80 kg/m³ enhanced the ultimate shear capacity of concrete by up to 70% compared with plain concrete. It was further observed that for fibre dosages above 40 kg/m³, the ultimate shear capacity of SFRC exceeded the cracking shear stress, demonstrating that fibres effectively suppressed brittle shear failure. The study proposed an empirical regression equation for predicting the shear capacity of SFRC based on compressive strength and fibre content, which has been adopted as a benchmark in subsequent shear prediction studies.

3. Khaloo and Afshari (2005) - Flexural Behaviour of SFRC Slabs

Khaloo and Afshari (2005) investigated the flexural behaviour of small steel fibre-reinforced concrete slabs, with particular attention to the effects of fibre volume fraction on load-deflection response, first-crack strength, and post-cracking toughness. Hooked-end fibres were incorporated at varying volume fractions, and slab specimens were subjected to uniformly distributed loading until failure.

The study reported that increasing fibre content produced significant improvements in post-cracking residual strength and flexural toughness. The crack-bridging mechanism of fibres was identified as the principal contributor to the enhanced post-peak response, delaying the coalescence of micro-cracks and extending the ductile response of the slab well beyond the point of first visible cracking. The findings affirmed that steel fibres are particularly effective in improving the serviceability performance of thin slab elements in which conventional bar reinforcement is impractical or inefficient.

4. **Banthia and Sappakittipakorn (2007) - Toughness Enhancement Through FibreHybridisation**

Banthia and Sappakittipakorn (2007) conducted an experimental programme to determine whether the toughness of SFRC incorporating large-diameter crimped fibres could be enhanced by partial replacement with smaller-diameter crimped fibres, while maintaining workability, fibre dispersibility, and cost competitiveness. Single-fibre and hybrid-fibre concrete mixes were produced and tested for fracture toughness using flexural beam specimens.

The results confirmed that replacing a proportion of large-diameter fibres with smaller-diameter equivalents significantly enhanced the fracture toughness of the composite without compromising workability. The study introduced the concept of fibre hybridisation as a cost-effective strategy for toughness improvement and concluded that FRC composites with initially low toughness were the most promising candidates for hybridisation. The principle of positive synergy in hybrid fibre systems—whereby the combined effect of two fibre types exceeds the sum of individual contributions—was clearly demonstrated by the experimental evidence.

5. **Yazıcı, *et al.,* (2007) - Effect of Aspect Ratio and Volume Fraction onSFRC**

Yazıcı,*et al.,* (2007) systematically investigated the effects of steel fibre aspect ratio (l/d) and volume fraction (Vf) on the compressive, split tensile, and flexural strengths and the ultrasonic pulse velocity of SFRC. Hooked-end bundled fibres with l/d ratios of 45, 65, and 80 were used at Vf values of 0.5%, 1.0%, and 1.5% in a 40 MPa base concrete, producing ten distinct mix designs for comparative assessment.

The study demonstrated that both l/d ratio and Vf significantly influenced split tensile and flexural strengths of SFRC, while compressive strength was only marginally affected. Steel fibres increased compressive strength by 4–19%, split tensile strength by 11–54%, and flexural strength by 3–81% relative to the control mix. The fibre aspect ratio exhibited an optimal value for each concrete batch beyond which further increases yielded diminishing returns. Mathematical expressions correlating l/d and Vf with mechanical properties were developed, providing practical design guidance for SFRC mix proportioning.

6. Altun, *et al.*, (2007) - Steel Fibre Addition to Mechanical Properties of RC Beams

Altun, *et al.,* (2007) studied the effect of adding Dramix hooked-end steel fibres at dosages of 0, 30, and 60 kg/m³ on the mechanical properties of C20 and C30 class concrete and on the flexural performance of full-scale reinforced concrete beams (300 × 300 × 2000 mm) tested under simple bending. Nine beams per concrete class, each with identical steel reinforcement, were tested under four-point loading.

Steel fibres produced only modest increases in compressive strength but markedly improved split tensile strength, flexural strength, and toughness. The energy absorption capacity of SFRC-reinforced beams increased up to five-fold at 60 kg/m³ compared with plain concrete beams, demonstrating the substantial improvement in ductility achievable through fibre addition. The enhancement in maximum moment capacity was comparatively small, confirming that the primary structural benefit of steel fibres in RC beams lies in their post-cracking energy absorption capacity rather than in peak load resistance.

7. Thomas and Ramaswamy (2007) - Mechanical Properties of SFRC

Thomas and Ramaswamy (2007) conducted a comprehensive evaluation of the mechanical properties of SFRC across a range of mix designs, fibre types, and volume fractions. The study examined how steel fibre addition affected compressive strength, split tensile strength, flexural strength, and modulus of elasticity for both normal- and high-strength concrete matrices.

The study established that steel fibres consistently improved tensile and flexural properties while having a smaller and less predictable influence on compressive strength. Empirical relationships between the fibre reinforcement index (defined as the product of Vf and l/d) and the resulting mechanical property enhancements were proposed and validated. The findings confirmed that the fibre reinforcement index is the key composite parameter governing SFRC strength improvements, providing a unified basis for comparing fibre systems of different geometry and content.

8. Afroughsabet and Ozbakkaloglu (2015) - Mechanical and Durability Properties of High-Strength SFRC

Afroughsabet and Ozbakkaloglu (2015) investigated the mechanical and durability properties of high-strength concrete (HSC) containing hooked-end steel fibres at four volume fractions (0.25%, 0.50%, 0.75%, 1.0%) and polypropylene fibres at three dosages (0.15%, 0.30%, 0.45%), both individually and in hybrid combinations at a total Vf of 1.0%. All mixes contained 10% silica fume as cement replacement. Compressive strength, splitting tensile strength, flexural strength, electrical resistivity, and water absorption were measured.

Steel fibres significantly enhanced splitting tensile and flexural strengths of HSC, with 1.0% steel fibre providing the highest mechanical performance overall. Among hybrid combinations, the mix containing 0.85% steel and 0.15% polypropylene fibre demonstrated the best overall performance. Substitution of steel fibres with polypropylene fibres reduced mechanical properties but improved durability indicators, as fibre addition reduced water absorption. The study confirmed that silica fume and steel fibres act synergistically to improve both mechanical and durability performance of HSC.

9. Abbass, *et al.,* (2018) - Mechanical Properties of SFRC Across Concrete Strengths

Abbass, *et al.,* (2018) systematically evaluated the mechanical properties of SFRC incorporating fibres of varying lengths and diameters across different concrete strength grades, defined by water-cement ratios. Direct tension, compressive, split tensile, and flexural strengths were measured at multiple fibre volume fractions. An analytical model for the compressive stress-strain behaviour of SFRC was developed and validated against experimental data.

Fibre content and length were found to have a significant combined effect on all measured mechanical properties, with increasing aspect ratio and dosage consistently enhancing splitting tensile strength. At 1.5% Vf, steel fibres were most effective in improving tensile performance. The proposed analytical model demonstrated good agreement with experimental stress-strain data, confirming the role of fibre length and diameter in governing the post-peak compressive response of SFRC. The study highlighted the interaction between concrete strength grade and fibre geometry in determining optimal reinforcement configurations.

10. Yoo, *et al.,* (2015) - Flexural Response of SFRC Beams Under Static and Impact Loading

Yoo, *et al.,* (2015) examined the flexural response of steel fibre-reinforced concrete beams under both quasi-static three-point bending and drop-weight impact loading, exploring the effects of concrete strength, fibre content, and strain rate. Both normal-strength and high-strength SFRC beams with varying fibre volume fractions were evaluated, with particular attention to post-cracking toughness and residual flexural strength.

Post-cracking flexural performance improved consistently with increasing fibre content across both static and impact loading regimes. High-strength SFRC beams exhibited reduced flexural toughness compared with normal-strength counterparts at equivalent fibre dosage, attributed to the stiffer matrix impeding fibre pull-out and thereby limiting energy absorption. Fibre orientation parallel to the tensile loading direction was confirmed to provide superior impact and tensile performance, underscoring the importance of fresh concrete workability and casting procedure on the structural effectiveness of SFRC.

11. Chen, *et al.,*(2022) - Shear Behaviour of SFRC Beams with High-Strength Reinforcement

Chen, *et al.,* (2022) conducted shear tests on eleven SFRC beams reinforced with high-strength steel bars, examining the interaction between steel fibre inclusion and stirrup ratio on shear performance. Fibre volume fractions of 0%, 0.5%, and 1.0% were investigated, and crack patterns, stirrup strains, and diagonal crack widths were monitored throughout loading up to ultimate failure.

Steel fibre inclusion increased overall stiffness, ultimate shear load, and failure deformation capacity relative to control beams. Fibres reduced stirrup strains and diagonal crack widths in the post-cracking regime, demonstrating a shear load-sharing mechanism between fibres and stirrups. The shear enhancement attributable to fibres decreased with increasing stirrup ratio, indicating that fibres and stirrups are partially substitutable and that hybrid design should be optimised considering their combined contributions. The study further noted a transformation in failure mode from brittle shear to ductile flexure with increasing fibre content.

12. El Bakzawy, *et al*., (2024) - Experimental investigation on the flexural behavior of SFRC beams reinforced with hybrid reinforcement schemes

El Bakzawy,*et al.,* (2024) carried out a comprehensive experimental programme on seven half-scale SFRC beams reinforced with hybrid longitudinal reinforcement schemes combining steel and glass fibre-reinforced polymer (GFRP) bars. Fibre volume fractions of 0%, 0.50%, and 1.00% were investigated under four-point bending, and load-carrying capacity, toughness, cracking load, ductility index, and failure mode were assessed.

Load-carrying capacity increased by 13% and 21% at 0.50% and 1.00% Vf, respectively. Energy absorption toughness was enhanced by 97.7% and 161% at the corresponding dosages, indicating a superlinear relationship between fibre volume fraction and toughness in the range studied. Fibres increased the first-crack load by 12.5–25% and reduced crack widths throughout the loading history. A modified first-principles model for predicting nominal flexural capacity of hybrid-reinforced SFRC beams, which explicitly accounted for fibre tensile forces in the cracked tension zone, achieved a predicted-to-experimental ratio of approximately 1.05.

13. Gong *et al*. (2023) - DIC Analysis of Hybrid Fibre-Reinforced Self-Compacting Concrete Beams

Gong *et al*. (2023) employed digital image correlation (DIC) technology to examine crack initiation, crack width development, and post-peak load resistance in hybrid steel fibre-reinforced self-compacting concrete beams with and without conventional longitudinal reinforcement bars. The study characterised the interaction between fibre-induced crack bridging and rebar-controlled crack spacing under four-point bending.

Fibre presence delayed crack initiation, reduced individual crack widths, and improved post-peak load resistance compared to beams without fibres. The combination of fibres with longitudinal reinforcement bars produced a more stable and gradual load-deflection response than either reinforcement system acting independently, confirming the scale-bridging synergy of the hybrid system. The stiffness enhancement attributable to fibres in the post-cracking regime reduced mid-span deflections under service loading, providing evidence for the serviceability benefits of fibre-rebar hybrid reinforcement.

14. Awad, *et al.*, (2023) - Hybrid Fibre RC Beams Under Flexure and Shear

Awad,*et al.,* (2023) investigated the flexural and shear behaviour of high-strength concrete beams reinforced with hybrid fibre combinations (steel and glass fibres) alongside conventional transverse steel bars. The study varied the span-to-depth ratio, fibre volume fractions, and stirrup configuration to assess their combined influence on failure mode, ductility, load capacity, and crack distribution.

The highest maximum deformation was recorded in beams containing both conventional transverse steel reinforcement (stirrups) and hybrid fibres, underscoring the complementary roles of both reinforcement types in lowering brittleness and enhancing inelastic deformation capacity. Adding 0.4% steel fibre with 0.2% glass fibre improved load-carrying capacity by 79.23% over the control specimen, with steel fibre identified as the dominant contributor to shear enhancement. Hybrid fibres distributed diagonal cracking over a greater length and prevented premature brittle shear failure, confirming fibres as effective shear reinforcement supplements.

15. Li *et al.* (2024) - Structural Performance of SFRC–Normal Concrete Composite Beams

Li *et al*. (2024) examined the structural performance of composite beams in which the tensile zone was cast from SFRC (at 0.5% and 1.0% Vf) and the compression zone from plain normal concrete. The layered arrangement was intended to maximise the benefit of steel fibres where tensile stresses were highest while limiting the associated cost and workability demands. Cracking load, yield load, ultimate load, and failure mode were the primary outcome measures.SFRC application in the tensile layer effectively improved all load measures compared to fully plain concrete reference beams, with the 1.0% Vf configuration consistently outperforming the 0.5% configuration. The failure mode shifted from abrupt concrete crushing in control beams to a more gradual progression of crushing accompanied by fibre pull-out, producing a more energy-absorbing and ductile response. The study confirmed that strategic placement of SFRC in the tensile zone can achieve significant structural benefits at reduced overall fibre content compared with full-section SFRC.

16. Wan *et al.* (2024) - Steel Fibre and Rebar Trade-Off in Tunnel Lining Segments

Wan *et al*. (2024) investigated the structural implications of varying steel fibre content while simultaneously reducing conventional rebar quantity in tunnel lining segments, comparing performance in shallow-buried and deep-buried configurations. The study sought to establish the extent to which fibres could substitute for conventional bar reinforcement without compromising crack control or load capacity.

Increasing steel fibre content while reducing rebar quantity reduced crack widths by 26% in shallow-buried segments and 18% in deep-buried segments relative to conventional designs.

The combined fibre-rebar system improved both initial crack load and compression ductility, with SFRC joints exhibiting significantly narrower crack widths than conventionally reinforced joints under equivalent loading. The results demonstrated that fibre and bar reinforcement can be traded off to achieve performance targets in segmental tunnel construction, offering potential for both material economy and constructability improvement.

17. Guo *et al.* (2025) - Bending Characteristics of SFRC Beams with Hybrid Bar Configurations

Guo *et al*. (2025) investigated the bending characteristics of SFRC beams reinforced with hybrid steel and GFRP bar configurations. The study examined the influence of fibre inclusion on crack initiation, crack width restriction, stiffness, and ultimate load capacity, and compared the performance of hybrid-fibre reinforced beams against normal concrete reference beams with identical bar reinforcement.Hybrid fibre inclusion delayed crack initiation, restricted crack widening, and increased load capacity by up to 13.2% compared to normal concrete beams. The stiffness of hybrid-fibre reinforced concrete beams lay between that of beams reinforced with steel bars alone and those reinforced with GFRP bars alone, reflecting the role of fibres in stiffening the tension zone in the post-cracking regime. The study reinforced the established understanding that fibres and bars act synergistically, with fibres improving crack control and bars providing primary tensile force transfer.

18. Adewuyi and Animbom (2024) - Characterisation of Steel Fibres for Crack Control and Strength Enhancement

Adewuyi and Animbom (2024) evaluated the optimal content and characterisation of steel fibres for impeding crack propagation and enhancing overall concrete strength, drawing on a comprehensive database of published experimental studies. The investigation systematically assessed the influence of fibre content, length, diameter, and volume fraction on the normalised compressive, flexural, and split tensile strengths of SFRC across normal- and high-strength concrete classes.

The study demonstrated that steel fibres improve tensile and flexural capacities in SFRC but may occasionally reduce compressive strength, particularly in high-strength concrete matrices where the stiffer matrix can restrict fibre pull-out. An optimal Vf of between 1.0% and 2.0% was identified for normalised strength improvement. Statistical performance ratings for different fibre geometries were established, and the study concluded that no single fibre type consistently outperforms all others across every strength property, highlighting the need for application-specific fibre selection and mix optimisation.

2.9.1 Summary of reviewed literature

The foregoing review of eighteen studies spanning six decades of research reveals a consistent and well-established body of evidence for the structural benefits of steel fibre reinforcement in concrete. Across all reviewed works, steel fibres have been shown to improve tensile and flexural strength, enhance post-cracking toughness and ductility, suppress crack initiation and propagation, and contribute to improved shear resistance and energy absorption capacity. The scale of improvement is consistently dependent on the fibre volume fraction, aspect ratio, fibre geometry, and concrete matrix strength, with optimal volume fractions generally identified in the range of 0.5% to 1.5% for normal-strength applications.

The literature further demonstrates that steel fibres act most effectively as complementary reinforcement alongside conventional steel bars, with the two systems operating at different scales of structural response: fibres controlling micro-crack formation and early-stage crack opening, and bars providing macro-scale tensile force resistance and structural ductility through yielding. This complementary interaction—characterised in the contemporary literature as a positive synergistic effect—forms the central conceptual basis of the hybrid reinforcement system investigated in the present research. Table 2.1 presents a consolidated summary of the findings from the reviewed literature.

Table 2.1: Summary of the findings from the Reviewed Literature

S/N	Author(s) & Year	Research Work	Final Findings
1	**Romualdi & Batson (1963)**	Investigated the mechanics of crack arrest in steel fibre-reinforced concrete, examining how closely-spaced fibres could inhibit crack propagation in cement matrices. The study provided an early theoretical and experimental foundation for SFRC, proposing that fibre spacing relative to crack tip stress intensity governed the cracking behaviour of the composite.	Demonstrated that decreasing the spacing between steel fibres significantly reduced crack widths and delayed crack propagation. Established the theoretical basis for the fibre-reinforced concrete concept, showing that wire reinforcement could substantially increase the tensile strength and post-cracking resistance of concrete.
2	**Khaloo & Kim (1997)**	Examined the influence of concrete matrix strength and fibre characteristics on the behaviour of SFRC under direct shear. Specimens made from normal- and high-strength matrices reinforced with	Found that increasing fibre volume fraction significantly improved the ultimate shear capacity of SFRC by up to 70% compared to plain concrete. Established that shear capacity was dependent

S/N	Author(s) & Year	Research Work	Final Findings
		hooked-end steel fibres at varying volume fractions were subjected to Z-type push-off shear testing.	on both compressive strength and fibre content, and proposed a regression-based equation for predicting ultimate shear stress of SFRC.
3	**Khaloo & Afshari (2005)**	Investigated the flexural behaviour of small-scale steel fibre-reinforced concrete slabs, studying the effects of fibre content on load-deflection response, first-crack strength, and post-cracking toughness. Hooked-end fibres were incorporated at varying volume fractions in slab specimens tested under uniform loading.	Reported significant improvements in post-cracking residual strength and flexural toughness with increasing fibre content. The crack-bridging action of fibres delayed coalescence of micro-cracks and extended the ductile response of the slabs well beyond the first crack load, demonstrating their effectiveness in enhancing slab serviceability.
4	**Banthia & Sappakittipakorn (2007)**	Explored whether the toughness of fibre-reinforced concrete incorporating large-diameter crimped fibres could be enhanced by partial substitution with smaller-diameter crimped fibres.	Confirmed that hybridisation of small- and large-diameter crimped steel fibres significantly enhanced fracture toughness of the composite. Concluded that replacing a portion of large-diameter fibres with smaller ones improved toughness synergistically, and that composites with low initial toughness benefited most from hybridisation.

S/N	Author(s) & Year	Research Work	Final Findings
5	**Yazıcı, *et al.*, (2007)**	Investigated the combined effect of fibre aspect ratio (l/d) and volume fraction (Vf) on the compressive, split tensile, and flexural strengths, and ultrasonic pulse velocity of SFRC. Hooked-end bundled fibres with l/d ratios of 45, 65, and 80 were used at volume fractions of 0.5%, 1.0%, and 1.5% in a 40 MPa base concrete.	Found that both l/d ratio and Vf significantly influenced split tensile and flexural strengths but had only a minor effect on compressive strength. Steel fibre inclusion increased compressive strength by 4–19%, split tensile strength by 11–54%, and flexural strength by 3–81% relative to the control. Mathematical expressions were developed to predict strength properties as a function of l/d and Vf.
6	**Altun, *et al.*,(2007)**	Investigated the effect of adding hooked-end steel fibres at dosages of 0, 30, and 60 kg/m³ on the mechanical properties of C20 and C30 class concrete and on the flexural performance of 300×300×2000 mm reinforced concrete beams tested under simple bending. Both plain concrete specimens and full-scale RC beams were evaluated.	Reported that fibre addition produced only modest gains in compressive strength but markedly improved split tensile strength, flexural strength, and toughness. RC beam toughness (energy absorption area under load-deflection curve) increased dramatically with fibre dosage—up to five-fold for beams at 60 kg/m³—while the enhancement in maximum moment capacity was relatively small.
7	**Thomas &**	Evaluated the mechanical properties of steel fibre-	Established that steel fibres consistently improved tensile

S/N	Author(s) & Year	Research Work	Final Findings
	Ramaswamy (2007)	reinforced concrete across a range of mix designs, fibre types, and volume fractions. The study systematically examined how fibre addition affected compressive strength, split tensile strength, flexural strength, and modulus of elasticity for normal- and high-strength concrete.	and flexural properties while having a smaller influence on compressive strength. Proposed empirical relationships between fibre reinforcement index and mechanical properties, confirming that the fibre reinforcement index (Vf × l/d) was the key parameter governing strength enhancements in SFRC.
8	**Afroughsabet & Ozbakkaloglu (2015)**	Examined the mechanical and durability properties of high-strength concrete incorporating hooked-end steel fibres (at 0.25%, 0.50%, 0.75%, 1.0% Vf) and polypropylene fibres (at 0.15%, 0.30%, 0.45%) individually and in combination at a total Vf of 1.0%. All mixes contained 10% silica fume. Compressive strength, splitting tensile strength, flexural strength, electrical resistivity, and water absorption were measured.	Steel fibres significantly enhanced splitting tensile and flexural strengths; 1.0% steel fibre provided the highest mechanical performance. Among hybrid combinations, the 0.85% steel + 0.15% polypropylene mix delivered the best overall performance. Substitution of steel with polypropylene fibres reduced mechanical properties but improved durability indicators. Addition of both fibre types reduced water absorption of concrete.
9	**Abbass, *et al.*, (2018)**	Evaluated the mechanical properties of SFRC incorporating fibres of varying lengths and diameters across	Fibre content and length had a significant combined effect on all mechanical properties. Increasing aspect ratio and

S/N	Author(s) & Year	Research Work	Final Findings
		different concrete strength grades defined by water-cement ratio. Direct tension, compressive, split tensile, and flexural strengths were measured at multiple fibre volume fractions. An analytical model for the compressive stress-strain behaviour was proposed.	fibre dosages consistently improved splitting tensile strength. At 1.5% Vf, steel fibres were most effective in enhancing tensile performance. The proposed analytical model showed good agreement with experimental stress-strain data, confirming the role of fibre length and diameter in governing compressive behaviour.
10	**Yoo, *et al.*,(2015)**	Investigated the flexural response of steel fibre-reinforced concrete beams under static and impact loading, focusing on the effects of concrete strength, fibre content, and loading rate. Both normal-strength and high-strength SFRC beams with varying fibre volume fractions were subjected to three-point bending and drop-weight impact tests.	Post-cracking flexural performance improved consistently with increasing fibre content. High-strength SFRC showed reduced flexural toughness compared to normal-strength SFRC at equivalent fibre dosage, attributed to the stiffer matrix resisting fibre pull-out. Impact resistance increased with fibre volume fraction, and fibres oriented parallel to the tensile load provided superior impact performance.
11	**Chen, *et al.*,(2022)**	Conducted shear tests on eleven SFRC beams reinforced with high-strength steel reinforcement bars, examining	Steel fibres increased overall stiffness, ultimate shear load, and failure deformation compared to control beams.

S/N	Author(s) & Year	Research Work	Final Findings
		the interaction between steel fibre inclusion and stirrup ratio on shear performance. Variables included fibre volume fraction (0%, 0.5%, 1.0%) and transverse reinforcement ratio. Crack patterns, stirrup strains, and diagonal crack widths were monitored.	Fibres reduced stirrup strains and diagonal crack widths in the post-cracking regime, indicating load-sharing between fibres and stirrups. The shear enhancement attributable to fibres decreased with increasing stirrup ratio, suggesting an interaction zone of optimal fibre-stirrup contribution.
12	**El Bakzawy, *et al.*,(2024)**	Conducted a comprehensive experimental programme on seven half-scale SFRC beams reinforced with hybrid longitudinal reinforcement schemes (steel and GFRP bars). Fibre volume fractions of 0%, 0.50%, and 1.00% were investigated. Load-carrying capacity, toughness, cracking load, ductility, and failure mode were assessed under four-point bending.	Load-carrying capacity increased by 13% and 21% at 0.50% and 1.00% Vf, respectively. Toughness was enhanced by 97.7% and 161% at the same fibre dosages, demonstrating a superlinear relationship between Vf and energy absorption. Fibre inclusion increased first-crack load by 12.5–25% and reduced crack widths throughout the loading history. A modified analytical model for nominal flexural capacity was validated.
13	**Gong *et al*. (2023)**	Performed digital image correlation (DIC) tests on hybrid steel fibre-reinforced self-compacting concrete beams with and without	Fibre presence delayed crack initiation, reduced crack widths, and improved post-peak resistance. The combination of fibres with

S/N	Author(s) & Year	Research Work	Final Findings
		longitudinal reinforcement bars to examine crack initiation, crack width development, and post-peak resistance. The interaction between fibre bridging and rebar crack regulation was characterised under four-point bending.	longitudinal bars produced a more stable load-deflection response than either system alone. Fibre-induced stiffness enhancement in the post-cracking regime reduced mid-span deflections under service loading, confirming the complementary structural roles of fibres and reinforcement bars.
14	**Awad, *et al.,* (2023)**	Investigated the flexural and shear behaviour of high-strength concrete beams with hybrid fibre reinforcement (steel and glass fibres) and conventional transverse steel bars. Variables included the span-to-depth ratio, fibre volume fractions, and the presence or absence of stirrups. Ductility index and failure deformation capacity were evaluated.	The highest maximum deformation was recorded in beams containing both transverse steel reinforcement and hybrid fibres. Adding 0.4% steel fibre with 0.2% glass fibre improved load-carrying capacity by 79.23% over the control. Hybrid fibres distributed diagonal cracking and prevented brittle shear failure. Decreasing span-to-depth ratio increased shear transfer through arch action but reduced ductility.
15	**Li *et al*. (2024)**	Investigated the structural performance of SFRC–normal concrete (NC) composite beams in which the tensile layer was cast from SFRC and the compression zone from plain	SFRC application in the tensile layer effectively improved cracking load, yield load, and ultimate load compared to reference beams with normal concrete. The

S/N	Author(s) & Year	Research Work	Final Findings
		concrete. Variables included SFRC layer thickness as a proxy for fibre content (0.5% and 1.0% Vf). Cracking load, yield load, ultimate load, and failure mode were evaluated.	1.0% Vf configuration consistently outperformed the 0.5% configuration in flexural resistance. Failure mode shifted from abrupt concrete crushing in normal concrete beams to a more gradual progression of crushing accompanied by fibre pull-out, enhancing energy absorption capacity.
16	**Wan *et al*. (2024)**	Examined the effect of varying steel fibre content while reducing conventional rebar quantity in tunnel lining segments on crack width, load-bearing capacity, and structural efficiency. Shallow-buried and deep-buried segment configurations were tested to assess the trade-off potential between fibre reinforcement and traditional bar reinforcement.	Increasing steel fibre content while reducing rebar quantity reduced crack widths by 26% in shallow-buried segments and 18% in deep-buried segments. The combination of fibres and bars improved both initial crack load and compression ductility. Results demonstrated that fibre and bar reinforcement can be traded off to achieve performance targets while potentially reducing material cost in tunnel applications.
17	**Guo *et al*. (2025)**	Investigated the bending characteristics of SFRC beams reinforced with hybrid steel and glass fibre-reinforced polymer (GFRP) bar configurations. The study examined how fibre	Hybrid fibre inclusion delayed crack initiation, restricted crack widening, and increased load capacity by up to 13.2% compared to normal concrete beams.

S/N	Author(s) & Year	Research Work	Final Findings
		inclusion modified crack initiation, crack widening, stiffness, and load capacity relative to conventionally reinforced normal concrete beams.	Stiffness of hybrid-fibre reinforced beams lay between that of steel-bar-only and GFRP-bar-only beams. The results confirmed the role of fibres in stiffening the tension zone in the post-cracking regime and the additive benefits of fibre-bar interaction.
18	**Adewuyi & Animbom (2024)**	Evaluated the optimal content and characterisation of steel fibres required to impede crack propagation and enhance overall strength of concrete.	Demonstrated that steel fibres improve tensile and flexural capacities but may occasionally reduce compressive strength, particularly in high-strength concrete matrices. Optimal fibre volume fraction for normalised strength improvement was identified at between 1.0% and 2.0%.

2.10 Research gaps and Relevance to the present study

Despite the substantial body of literature on steel fibre–reinforced concrete systems, several research gaps remain that are directly relevant to the experimental objectives of the present study. First, many existing experimental programmes have investigated steel fibre reinforcement in normal-strength concrete (C20 – C40 class), but fewer studies have systematically evaluated and compared plain conventional concrete and steel fibre–

reinforced concrete within the same experimental framework using identical mix designs and testing conditions. Such direct comparisons are essential for clearly quantifying the contribution of steel fibres to mechanical performance. Secondly, most published work tends to focus primarily on flexural behaviour under monotonic loading, while the compressive behaviour and the interaction between compressive and tensile failure modes in steel fibre–reinforced concrete remain less thoroughly characterised. A more integrated assessment of how fibres influence both pre-cracking and post-cracking behaviour across different loading conditions is still required. Thirdly, the effects of fibre volume fraction - particularly within the range of 0.5–1.5% - on the full suite of mechanical properties, including compressive strength, split tensile strength, flexural strength, and ductility of fibre-reinforced concrete, have not been comprehensively documented in a single, unified experimental study. This limits the ability to establish clear performance trends and design recommendations.

The present research addresses these gaps by investigating the mechanical properties—specifically compressive strength, split tensile strength, flexural strength, and load–deflection behavior-of concrete specimens reinforced with steel fibres and plain concrete without fibres, using a consistent experimental framework. The findings are intended to provide quantitative evidence of the improvement brought about by steel fibre reinforcement and to support more informed decisions in structural concrete design and application. The literature reviewed in this section provides the conceptual foundation and comparative context against which the experimental results of the current study will be interpreted.

CHAPTER THREE

METHODOLGY

3.1 Materials Used for the Study

The coarse aggregate used in this research study were crushed granite of igneous origin. They come in different sizes but the size used for this research was 12.5mm, sourced from a quarry in Ikpeshi, Auchi Ikpeshi road, Edo State. The fine aggregate used in this research study was river sandobtained from river bed. It was confirmed to be salt-free not like sand got from the lagoon (salt content is high). The sand particles were sieve which was free from clay, loam, dirt and organic or a chemical matter of any description. The particles that pass through BS sieve No. 4 (aperture 2.36mm) but retained on sieve No. 220 (aperture 0.06mm) ensuring that the dust particles were removed from the sand (BS EN 933-1).Ordinary Portland cement (OPC) with properties conforming to those specified in the British Standard code (BS 12, 1971) was used for the production of concrete and ensures that the cement passes test for which its properties maybe determined. This brand of cement has a medium hardening rate and it is according to the Nigeria Industrial standard specification (NIS 441-1:2003 and NIS 441-2:2003 for Ordinary Portland Cement) suitable foremost concrete work. The cement, supplied in 50kg bags was well protected from dampness to avoid lumps. Approximately 85% to 95% of cement particles are smaller than 45um, with the average particle around 15um and the particle density from 3.10g/cm to 3.25g/cm^3. The mix proportion of cement in concrete production has a major effect on the properties of the concrete, mostly the strength of the concrete. The water used was obtained from the laboratory taps. The water was portable and did not contain any sulphates, ferric, alkaline, oils, vegetation or salt that could affect the properties of the materials or concrete in the fresh or hardened state (Annex A of BS 3148:1980). Also the water was colorless, tasteless, odorless and free from decaying organic matters. Stainless fibers used were industrial waste of high-grade stainless steel with four sided strands, giving to cleaning edges to handle toughest jobs. Since each chip is made of a single strand of stainless steel, they will not tear or splinter. Also, they will not corrode. It has a good tensile strength and the fiber strips length vary but the 1.5 and 2 inches long fibres were used. The steel fibers used were gotten from the mechanical engineering laboratory of Auchi polytechnic, Auchi, Edo State, Nigeria. The plywood type-formwork was prepared into aspecific designed size for concrete beam (150 mm x 150mm x 750m) (BS EN 12390-5:2019 and ASTM C78).

3.2 Equipment and Tools for the Study

The equipment used was mainly those available in the Structures and Concrete Laboratory of the Department of Civil Engineering at Auchi polytechnic, Auchi, Edo State, Nigeria. A brief description of the equipment to be used in the course of the investigation is shown below.

a) **Weighing machine:** a weighing scale with a 0-50kg capacity was utilized to measure concrete constituents and other project materials. The scale features a vertical measuring gauge with a loading platform attached to its back

b) **Cube mould:** made of cast iron with inner dimensions of 750x150x150mm they have a sheet metal base and they were well greased to prevent excessive moisture escape and facilitate for easy de-molding:

c) **Concrete mixer:** which is a diesel engine powered tilting drum mixer. It has a single cylinder engine as well as a mobile rotating drum which rotates in order to ensure proper mixing of constituent materials thereby creating a homogeneous concrete mix; Compression Testing Machine which is a hydraulically – operated equipment. It consists of a measuring gauge with two indicators or pointers (black and red). The indicators must be set to zero marks before testing. The load is applied to a test specimen through two steel loading platforms; a fixed upper platform and an up warding moving the lower platform. The lower platform has markings which help in centralizing a test specimen to receive the concentric load: Wheel Barrow used to transfer large masses of aggregates and tested specimens: Tapping Rod used to compact the concrete in the cube moulds; and Sieves used to obtain the grain size classification of aggregates.

The other equipment used in this project includes: Trowels, Drying Ovens, Shovels, Head pan, Buckets, Steel rule, Curing tank, Tray

3.3 Experimental Procedures

The experimental procedure will begin with the preliminary investigation on the sand, and then the compressive strength determination of 150mm concrete cubes and ends with the tensile strength determination of 150mm by 300mm high concrete cylinders. The preliminary investigation carried out is to determine the properties of each material. The tests include: sieve analysis, specific gravity, bulk density, dry density, and moisture content. The secondary investigations carried out in the course of this research study include the following: slump test (workability), and compressive strength test,

3.3.1 Sieve Analysis/Gradation of Aggregates

Sieve analysis is the name given to the simple operation of dividing a sample of aggregates into the fraction, each consisting of particles of approximately the size. Before this experiment, the aggregates (sand and granite) were dried sufficiently to avoid lumps of fine particles being classified as the large particle (in the case of sand and to prevent clogging of finer sieves).

Apparatus: Mechanical Sieve Shaker, Sieve brush, weighing balance, Various Sizes of Sieve, ranging from 2.36mm - 65µm, drying oven and evaporating pans.

Procedure:

a. The sieves were arranged in a stack with the largest sieve size (2.36 mm) placed at the top and the remaining sieves arranged below in descending order of aperture size. A receiver (pan) was placed beneath the smallest sieve to collect the fine particles that passed through all the sieves.
b. The weighed soil sample was carefully transferred into the topmost sieve, and a lid was placed on top of the sieve stack to prevent loss of material during shaking.
c. The nest of sieves was agitated using both lateral and vertical motions, accompanied by a gentle jarring action to ensure that the soil particles moved continuously across the sieve surfaces. This agitation was carried out for 10 minutes. When a mechanical or electric sieve shaker was used, the sieve stack was placed in the machine and shaken for 15 minutes.
d. After the initial shaking period, each sieve was removed individually and shaken manually over a clean tray to ensure that no additional particles passed through the sieve openings.

e. The soil retained on each sieve was carefully collected and weighed separately using a weighing balance.
f. The mass of soil retained on each sieve was recorded, and the data was later used to determine the particle size distribution of the soil sample.

3.3.2 Specific Gravity

Specific gravity is the ratio of the density of a substance to the density (mass of the same unit volume) of a reference substance. Apparent specific gravity is the ratio of the weight of a volume of the substance to the weight of an equal volume of the reference substance.

The specific gravity of a soil is often used to describe the relationship between the weight of soil and its volume. As soil contains different particles with different specific gravities; the term Gs represents an average value for all the particles.

Apparatus: Density bottle, Glass rod, Wash bottle containing distilled water and Drying Oven.

Procedure:

a. The dried density bottle was weighed and the weight was recorded as W_1.
b. About 25.0 g of the oven-dried soil material was obtained and transferred into the density bottle. The stopper was replaced and the bottle with its contents was weighed. The weight was recorded as W_2.
c. Distilled or tap water was added until the soil in the bottle was just covered. The mixture was thoroughly stirred with a glass rod or shaken to remove any air trapped in the soil.

d. The bottle was then completely filled with distilled or tap water and the stopper was replaced. The density bottle and its contents were carefully shaken to remove any remaining air. The weight was recorded as W_3.

e. The contents of the bottle were emptied, and the bottle was washed thoroughly. It was then filled with distilled water only and weighed. The weight was recorded as W_4.

The equation for the computation of specific gravity is shown in equation 3.1

$$G_s = \frac{W_2 - W_1}{(W_4 - W_1) - (W_3 - W_2)} \qquad (3.1)$$

Where;

G_s **Specific Gravity**

Sand: Mass of empty density bottle = W_1

Mass of density bottle + dry specimen = W_2

Mass of density bottle + dry specimen + water = W_3

Mass of density bottle + water = W_4

Mass of water used = $(W_3 – W_2)$

Mass of sample = $(W_2 – W_1)$

Volume of sample = $(W_4 - W_1) - (W_3 - W_2)$

Granite: Mass of empty density bottle = W_1

Mass of density bottle + dry specimen = W_2

Mass of density bottle + dry specimen + water = W_3

Mass of density bottle + water = W_4

Mass of water used, $(W_3 - W_2)$ = 3169g - 2069g

Mass of sample, (W_2 - W_1

Volume of sample, (W_4 - W_1- (W_3 - W_2))

W1 = Weight of bottle

W2 = Weight of bottle and dry

W3 = Weight of bottle, soil and water

W4 = Weight of bottle filled with water only.

The specific gravity is used in the laboratory to help with the calculation of the void ratios of soil specimens, in the determination of the moisture content of a soil, and in the particle-size analysis, also known as the sedimentation test.

The procedure and calculations follow international recognized codes and standards;

ASTM D854-Standard Test Method of Specific Gravity of Soil Solid by Water psynometer

BS 1377: Part 2(1990)- Methods of Test of Soils for Civil Engineering Purposes-classification Test

AASHTO T100- Specific Gravity of Soils

3.3.3 Bulk Density

The apparatus includes a cylindrical metal container of approximately 15 or 30-litre capacity. The volume of the metal container is first obtained by determining the weight of water required to fill it. The container is then filled to overflowing with aggregate being discharged from a height of not more than 50mm above the top of the container. The aggregate in the container is then weighed and divided by the volume of the container to give the bulk density in kg/m3.

Apparatus:

A 6” (150mm) diameter open-ended steel cylinder with plunger and base plate, a standard metal, tamping rod, Weigh balance, B.S. test sieves 1/2” (12.5mm) and 3/8” (9.8mm) and A compression testing machine

3.3.4 Moisture content

Water content or moisture content is the quantity of water contained in a material. It is the ratio of water present in the soil mass to the weight of the soil solids.

The aggregate specimen of sand was weighed and placed in the oven for 24 hours, then weighed when removed from the oven. The decrease in weight of the specimen shows the corresponding loss of moisture content and it is expressed in percentage.

3.3.5 Dry Density Test

The moisture content of the sample was first determined. Then, the sample was placed in a mould and weighed. The volume and weight of the mould were also determined. The bulk density (γ) was calculated by dividing the mass of sample by the volume of the mould as shown in equation 3.2

$$\text{Dry density} = \frac{\gamma}{1+w} \qquad (3.2)$$

3.3.6 Aggregate Crushing value and Impact value

Aggregate Crushing value: The material for this test consists of aggregate passing the 14mm B.S. test sieve and retained on the 10mm B.S. test sieve and tested in a surface-dry condition. The apparatus required for this test consists of an open-ended steel cylinder of normal size 150 mm internal diameters with plunger and base plate. The approximate quantity may be found conveniently by filling the cylindrical measure in three layers, each layer being tamped 25 times from a height of about 50mm above the surface of the aggregate with the rounded end of the rod and finally leveled off. Record the mass (weight) of the sample (W1). Insert the plunger so that it rests horizontally on this surface.

Place the apparatus between the platens of the testing machine and applied a load of 399.5KN. (40ton) Release the load and remove the crushed material into a clean tray. Sieve the whole of the sample on the No. 7 (2.36mm) B.S. test sieve. Weigh the fraction passing the sieve (W2). The ratio of the mass of fines formed to the total mass of the sample expressed as the percentage is the aggregate crushing value as shown in equation 3.3

Percentage fines = $\frac{w_1 - w_2}{w_2} \, x \, 100$ (3.3)

This value is usually not greater than 30%.

Aggregate Impact Value: The aggregate impact value gives a relative measure of the resistance of an aggregate to sudden shock or impact, which usually differs from its resistance to a slowly applied compressive load. The aggregate impact value is usually not more than 30. The standard aggregate impact test is made on aggregate passing a 14mm B.S. sieve and retained on a 10mm sieve. The impact test machine is a circular metal base weighing between 22kg and 30kg with a plane lower surface of not less than 300mm diameter. The device features a steel cup and a heavy metal hammer (13.5-14kg) with precise dimensions, designed for controlled impact testing. The hammer is raised and dropped from a specified height (380mm) within vertical guides, with an optional automated system for tracking the number of blows. To conduct the test, surface-dry aggregate is compacted in the machine's cup with 25 blows of a tamping rod and weighed (W1). The cup is then secured, and the aggregate is subjected to 15 impact blows. After crushing, the entire sample is sieved over a 2.36mm sieve, and the weight of the material passing through (W2) is recorded. The percentage of fine material is calculated as the ratio of the mass passing the 2.36mm sieve to the total sample mass as shown in equation 3.4

$$\frac{W1}{W2} \times 100 \qquad (3.4)$$

Where

W1 is the mass of fraction passing the sieve for separating the fine (g).

W2 is the mass of surface dry sample (g).

3.4 Secondary Investigation

The secondary investigations carried out in the course of this research study include the following: Slump test (workability), Compressive strength test, Split Cylinder test, Flexural Strength Test.

3.4.1 Slump Test

The concrete slump test is an empirical test that measures the workability of fresh concrete. It measures the consistency of the concrete in that specific batch. This test is performed to check the consistency of freshly made concrete. Consistency is a term very closely related to workability. It is a term which describes the state of fresh concrete. It refers to the ease with which the concrete flows. It is used to indicate the degree of wetness.

Apparatus: Mould, Tamping rod: (16mm diameter, 600mm long and rounded at one end), Steel rule, Stopwatch, Hand trowel and Head pan

Procedure:

The surface of the slump mould was first cleaned thoroughly to remove any dirt or hardened concrete. The mould was then placed on a smooth, horizontal, rigid, and non-absorbent surface. Care was taken to ensure that the location of the test was free from vibration or disturbance that could affect the accuracy of the results.

A concrete mix with a ratio of 1:2:4 (cement: sand: granite) was prepared. The maximum size of the coarse aggregate used was 19 mm, and a water–cement ratio of 0.55 was adopted to obtain the required consistency for the test.

The slump mould was held firmly in position to prevent movement during filling. The prepared concrete was then placed into the mould in three equal layers, with each layer occupying approximately one-third of the total height of the mould.

Each layer of concrete was compacted by tamping it 25 times using the rounded end of a tamping rod. The strokes were applied carefully and uniformly across the entire cross-section of the mould to ensure proper compaction.

For the second and third layers, the tamping rod was allowed to penetrate slightly into the underlying layer in order to ensure proper bonding between the layers. The bottom layer was tamped throughout its entire depth to achieve uniform compaction.

After the top layer had been tamped, additional concrete was added where necessary so that the mould was completely filled. The surface of the concrete was then struck off and finished level with the top of the mould using a trowel to obtain a smooth and even surface.

Any mortar or concrete that leaked out between the mould and the base plate during filling and tamping was carefully cleaned away to maintain a neat working area.

Finally, the slump value and the type of slump observed were measured and recorded as part of the test results.

3.4.2 Compressive Strength Test

The compressive strengths for the cubes (150mm cube) of hardened concrete were determined by using a Compression Machine of 1500kN capacity. The method for the determination of compressive strength is according to BS 1881-116:1983. Compressive strength remains the most important properties of structural concrete. In cases where strength in tension or in shear is of primary importance, the compressive strength is frequently used as a measure of these properties. The loading should be within the range of 0.2N/(mm^2sec) to 0.4N/(mm^2sec) as described in this standard. However, the loading rate of 0.25N/(mm^2sec) was used. Annan and Azwan (2001). The tests were carried out at the ages of 7, 14, 21and 28 days. Results report the average of the three samples.

After 7 days of curing three samples were tested using compressive test machine and the other three at 14, 21 and 28 days respectively. The cube carefully placed at the centre on the lower platen of the testing-machine and ensures that the load will be applied to two opposite cast faces of the cube. The load will then be applied at appropriate limit indicated on the testing machine. The compressive strength of each cube is calculated by dividing the maximum load by the nominal cross-sectional area. The strength is expressed in N/mm^2.

$$f_c = \frac{P}{A} \qquad 3.5$$

Where:

$f_c$is compressive strength (N/mm^2or MPa)

P is maximum load at failure (N)

A is cross-sectional area of specimen (mm^2)

3.4.3 Split Cylinder test:

Split cylinder testis use to determine the splitting tensile strength of concrete.

$$f_t = \frac{2P}{\pi LD} \qquad 3.6$$

Where:

f_t is split tensile strength (N/mm^{2}or MPa)

P is maximum load at failure (N)

L is length of cylinder specimen (mm)

$D$is diameter of cylinder specimen (mm)

π = 3.142

Apparatus

Compression testing machine, tamping bar, moulds, two packing strips of plywood 30 cm long and 12mm wide.

Procedure:

a. The concrete specimen was removed from the curing tank after it had been cured in water for 7 days.
b. The surface of the specimen was carefully wiped with a clean cloth to remove any excess water present on it.
c. Diametrical lines were then drawn on the two circular ends of the specimen in order to ensure that both lines lay along the same axial plane, which helped in proper alignment during testing.

d. The weight and dimensions of the specimen were measured and recorded before carrying out the test.
e. The compression testing machine was set to the appropriate loading range required for the test.
f. A plywood strip was placed on the lower plate of the compression testing machine, and the specimen was carefully placed on top of it.
g. The specimen was then properly aligned so that the diametrical lines drawn on its ends were positioned vertically and centered over the bottom plate to ensure that the load would be applied along the correct axis.
h. Another plywood strip was placed on top of the specimen to distribute the load evenly during the test.
i. The upper plate of the compression testing machine was gradually lowered until it made contact with the top plywood strip.
j. The load was applied continuously and gradually without any shock until the specimen failed.
k. Finally, the maximum load at failure (breaking load, P) was observed and recorded for further calculations.

3.4.4 Flexural Strength test:

Flexural strength testis use to determine the flexural strength of concrete. It evaluates the tensile strength of concrete indirectly. It tests the ability of unreinforced concrete beam or slab to withstand failure in bending. The results of flexural test on concrete expressed as a modulus of rupture which denotes as (MR) in MPa or psi. The flexural test on concrete can be conducted using either three-point load test (ASTM C78) or center point load test (ASTM C293).

$$f_r = \frac{PL}{bd^2} \qquad 3.7$$

Where:

f_r isflexural strength (N/mm^{2}or MPa)

P is maximum load at failure (N)

L is span length (mm)

$b$is width of specimen (mm)

$d$is depth of specimen (mm)

Apparatus:

a. Steel, iron cast, or other non-absorbent material molds with size of 150mm x 150mm x750mm)
b. Tamping rods: ASTM specify large rode (16mm diameter and 600mm long) and small rode (10mm diameter and 300mm long)
c. Testing machine capable of applying loads at a uniform rate without interruption of shocks
d. Scoop
e. Trowel
f. Balance with accuracy of 1g
g. Power driven concrete mixer

Procedure:

a. The test was carried out on the concrete specimen immediately after it was removed from the curing condition in order to prevent surface drying, which could reduce or affect the flexural strength of the specimen.
b. The specimen was carefully placed on the supporting loading points of the flexural testing machine. The hand-finished surface of the specimen was positioned so that it did not come into contact with the loading points. This arrangement ensured proper and acceptable contact between the specimen and the loading supports.
c. The loading system of the testing machine was then properly centered in relation to the applied force so that the load would be applied symmetrically on the specimen.
d. The block used to apply the load was gradually lowered until it made proper contact with the surface of the specimen at the designated loading points.
e. A small preliminary load, ranging between 2% and 6% of the computed ultimate load, was applied in order to stabilize the specimen and ensure proper seating before the main loading began.
f. Using 0.10 mm and 0.38 mm leaf-type feeler gauges, the contact surfaces between the specimen and the load-applying blocks as well as the support blocks were examined. This was done to determine whether any gap existed that was greater or smaller than the specified gauge thickness over a length of 25 mm or more.
g. Where any gap greater than 0.10 mm was detected, it was eliminated by inserting leather shims measuring approximately 6.4 mm thick and 25–50 mm long. The shims were placed so that they extended across the entire width of the specimen to ensure proper load distribution.

h. If the gap between the specimen and the loading or support blocks exceeded 0.38 mm, the specimen was either capped or ground in order to remove the excessive gap and achieve a more uniform contact surface.
i. Finally, the load was applied continuously and without shock until the specimen failed. The loading was maintained at a constant rate, in accordance with the Indian Standard specification, which recommended a loading rate of 400 kg/min for a 150 mm specimen.

3.5 Composition of Concrete Mix

A water-cement ratio 0.55 was used. And the mix proportion by weight was1:1½:3 (cement: fine aggregate: coarse aggregate). The specimens made and their dimensions are namely the cube (150mm x 150mm x 150mm), cylinder (300mm x 150 diameter) and beams (150mm x 150mm x 750mm) cured and crushed for 7 days, 14 days, 21 days and 28 days. The prescribed mix proportion was used i.e. the mixes were specified by weight and are given inBS 8110 (Structural Use of Concrete). Materials were mixed at ambient temperature using a rotating pan type mixer. Mixing of the constituent materials was undertaken for six and a half minutes with mixing conforming to BS 1881-125:1986.

3.6 Moulding and Demoulding

Concrete cubes (150mm) have been moulded according to British Standard (BS 1881). Prefabricated concrete cube moulds of the required specimen sizes were oiled lightly. The prepared concrete was then poured into the moulds. The test cubes were stripped from the moulds after 24 hours and then submerged in a tank with water maintained at 20 – 3**9**˚C for curing.

3.7 Method of Curing

Curing begins after the exposed surfaces of the concrete have hardened sufficiently to resist marring. Curing ensures the continued hydration of cement so that the concrete continues to gain strength. The curing process is part of the chemical reaction between cement and water to hydrate the product, creating a gel that can be laid down only in water-filled space. It usually involves the control of moisture loss and the temperature affecting the hydration process. The curing process is vital to quality and has a strong influence on concrete properties such as durability, strength, water tightness, resistance, volume, and freezing and thawing resistance.

The method used to cure the concrete is the water curing method by immersion in water preventing excessive loss of moisture where the concrete cubes are covered with a layer of water in curing tank for period of 7, 14, 21 and 28days. This technique is used to control the evaporation of moisture from the surface and the concrete gradually produces its chemical reaction that will eventually harden the concrete. This is by far the best method of curing as it satisfies all the requirements of curing, namely, promotion of hydration, elimination of shrinkage and absorption of the heat of hydration.

3.8 Materials Calculation

Table 3.1 shows the total number of concrete cubes, cylinders and beams with a water-binderratio of 0.55 tested for.

3.1 Table 3.1: Numbers of concrete cube samples cast

Percentage Steel fibre	**Weight of Fibre (Kg)**	**Number of Concrete Cubes**				
		7 days	14 days	21 days	28 days	Total
0%	0	3	3	3	3	12
2.5%	220.91	3	3	3	3	12
5%	441.82	3	3	3	3	12
7.5%	662.73	3	3	3	3	12
10%	883.64	3	3	3	3	12
		Total number of concrete cubes = 60				

Table 3.1 presented the number of concrete cube samples that were cast for different percentages of steel fibre added to the concrete mix. The steel fibre content varied from 0% to 10%, and the concrete cubes were prepared to be tested at 7, 14, 21, and 28 days curing periods. For the control mix (0% steel fibre), a fibre weight of 88.36 kg was recorded in the table. For this percentage, three concrete cubes were cast for each curing age of 7, 14, 21, and 28 days, giving a total of 12 cubes for this mix. These cubes served as the reference samples for comparing the effect of steel fibre addition on the properties of concrete. At 2.5% steel fibre content, the weight of fibre used increased to 220.91 kg. Similar to the control mix, three cubes were produced for each curing period (7, 14, 21, and 28 days). For 5% steel fibre addition, the weight of fibre further increased to 441.82 kg. These specimens helped in assessing the performance of concrete at moderate steel fibre content. When the steel fibre content was increased to 7.5%, the fibre weight used was 662.73 kg. These cubes were used to examine the effect of higher fibre content on concrete properties. Finally, for

10% steel fibre content, the fibre weight increased to 883.64 kg. These samples were intended to evaluate the performance of concrete with the highest fibre percentage used in the experiment.

Table 3.2: Numbers of concrete cylinder samples cast

Percentage Steel fibre	Weight of Fibre (Kg)	Number of Concrete Cylinder				
		7 days	14 days	21 days	28 days	Total
0%	0	3	3	3	3	12
2.5%	346.91	3	3	3	3	12
5%	693.82	3	3	3	3	12
7.5%	1040.73	3	3	3	3	12
10%	1387.60	3	3	3	3	12
		Total number of concrete cylinder = 60				

Table 3.2 showed the number of concrete cylinder samples that were cast for different percentages of steel fibre used in the concrete mix. The steel fibre content varied from 0% to10%**,** and the cylinders were prepared for testing at 7, 14, 21, and 28 days curing periods. For the control mix (0% steel fibre)**,** a fibre weight of 137.73 kg was recorded. For this mix, three concrete cylinders were cast for each curing age (7, 14, 21, and 28 days), giving a total of 12 cylinders**.** At 2.5% steel fibre**,** the fibre weight increased to 346.91 kg. For the **5%** steel fibre content, the fibre weight was 693.82 kg. When the steel fibre content increased to 7.5%**,** the fibre weight rose to 1040.73 kg. For the 10% steel fibre content**,** the fibre weight was 1387.60 kg.

Table 3.3: Number of Concrete beams cast

Percentage Steel Fibre	Weight of Fibre (Kg)	Number of Concrete beams		
		7 days	28 days	Total
0%	0	3	3	6
2.5%	552.27	3	3	6
5%	1104.55	3	3	6
7.5%	1656.20	3	3	6
10%	2207.10	3	3	6
		Total number of concrete beams = 30		

Table 3.3 presented the number of concrete beam samples that were cast for different percentages of steel fibre used in the concrete mix. The steel fibre content ranged from 0% to 10%, and the beams were prepared for testing at 7 days and 28 days curing periods. For the control mix (0% steel fibre), a fibre weight of 220.91 kg was recorded. For this mix, three beams were cast for 7 days curing and three beams for 28 days curing. At 2.5% steel fibre content, the fibre weight increased to 552.27 kg. For the 5% steel fibre mix, the fibre weight was 1104.55 kg. When the steel fibre content was increased to 7.5%, the fibre weight rose to 1656.20 kg. For the 10% steel fibre mix, the fibre weight was 2207.10 kg.

Materials calculation for concrete cubes

Volume of a single concrete cube = (150 x 150 x150) mm^3 = 3375000mm^3 = 0.003375m^3

Concrete cube mix ratio = 1:1½:3 (1 for cement, 1½ for sand and 3 for coarse aggregate) = 5.5

Weight of components = $\frac{\text{ratio of component}}{\text{total ratio}}$x total volume x density of concrete

Density of Concrete= 2400 kg/m^3 Number of Cubes=60

Weight of Cement= (1/5.5) x0.003375x2400x60= 88.36kg

Weight of Fine aggregates = (1.5/5.5) x0.003375x2400x60= 132.35kg

Weight of coarse aggregates=(3/5.5) x0.003375x2400x60= 265.10kg

Weight of fibre (2.5%) = (2.5/5.5) x 0.003375x2400x60= 220.91kg

Materials calculation for concrete cylinders

Volume of a single concrete cylinder = (πx150^{2}x0.25x300) mm^3 = 5301437.6mm^3 = 0.0053m^3

Concrete cylinder mix ratio =1:1½:3 (1 cement, 1½ sand and 3 coarse aggregate) = 5.5

Weight of components = $\frac{\text{ratio of component}}{\text{total ratio}}$x total volume x density of concrete

Density of Concrete= 2400 kg/m^3 Number of Cylinders=60

Weight of Cement= $\frac{1}{5.5}$x0.0053x2400x60= 138.76kg

Weight of Fine aggregates = $\frac{1.5}{5.5}$x0.0053x2400x60= 208.15kg

Weight of coarse aggregates=$\frac{3}{5.5}$x0.0053x2400x60= 416.29kg

Weight of fibre (2.5%) =$\frac{2.5}{5.5}$x 0.0053x2400x60= 346.91kg

Materials calculation for concrete beams

Volume of a single concrete cylinder = (150 x 150 x750) mm^3 = 16875000 mm^3 = 0.016875m^3

Concrete beam mix ratio = 1:1½:3 (1 for cement, 1½ for sand and 3 for coarse aggregate) = 5.5

Weight of components = $\frac{\text{ratio of component}}{\text{total ratio}}$x total volume x density of concrete

Density of Concrete= 2400 kg/m3   Number of Cylinders=30

Weight of Cement= $\frac{1}{5.5}$x0.016875x2400x30= 220.91kg

Weight of Fine aggregates = $\frac{1.5}{5.5}$x0.016875x2400x30= 331.36kg

Weight of coarse aggregates=$\frac{3}{5.5}$x0.016875x2400x30= 662.73kg

Weight of fibre (2.5%) =$\frac{2.5}{5.5}$x 0.016873x2400x30= 552.27kg

Table 3.4 outlines the quantities of cement, fine aggregate and coarse aggregate used for various concrete specimens, including cube, cylinders, and beams.

Table 3.4: Weights of each component under each section

	Weight of Fibre at 2.5 (Kg)	**Weight of cement (kg)**	**Weight of fine aggregate (kg)**	**Weight of coarse aggregate (kg)**
Concrete cubes	220.9	88.36	132.35	265.10
Concrete cylinder	346.91	188.70	208.15	416.29
Concrete beams	552.27	220.91	331.36	662.73
Total	1115.08	497.97	671.86	1344.12

The calculations were made on exact values required. Allowance were made for wastage and losses but they were also all in the ratios as shown so as not to affect the components of the concrete mix and were also within reasonable limits so as not to affect the cost carrying out the project.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Specific Gravity Test (Gs)

A specific gravity refers to the actual particles which make up the soil mass. The term 'specific gravity' as it used here refers to particles as they occur naturally. This sometimes called the apparent specific gravity. The specific gravity of a soil is the ratio of the weight or mass of a volume of the material to the weight or mass of an equal volume of water. For soils, it is specified to use one-liter gas jar fitted with a rubber bung and a mechanical shaker apparatus which rotates the jar at a constant rate. An oven dried sample was placed into the gas jar along with some 500ml of water. The jar was sealed and shaken. Subsequently, following established procedures, specific gravity of the soil can be calculated. The tests were performed as per procedures laid out in BS1377: part 2: 1990 and BS EN 1997: part 2: 2007.

The Specific gravity of sand is 2.63, for granite is 2.66

4.1.1 Sieve Analysis

A particle size distribution analysis is a necessary test for soils, especially coarse soils that is presents in relative proportions of different sizes of particles. Through this analysis, it is possible to determine whether the soil consists of predominately gravel, sand, silt or clay sizes and to a limited extent which of these size ranges is likely to control the engineering properties of soil. Sieve analysis was performed to determine the soil particle size distribution. Representative sample of approximately 100g was used for the test. The sample was washed using the BS 200 sieve and the fraction retained on the sieve was oven dried and used for the sieve analysis. The sieving was done by mechanical method using an automatic shaker and a set of sieves. The fractions retained on each sieve were then weighed and their percentage weights calculated. The result of this test is used for classification purposes, and it enables soil groupings to be delineated and their properties inferred. The test was carried out in accordance with BS EN 1997-2-2007.Table 4.1 shows the sieve analysis of coarse aggregate (Granite).

Table 4.1: Sieve Analysis for Fine Aggregate (Sand)

WEIGHT OF TEST SAMPLE= 1200g				
BS Sieve Size (mm)	**Weight Retained (g)**	**Percentage Retained (%)**	**Cumulative Retained (%)**	**Percentage Passing (%)**
10mm	0	0	0	100.00
5mm	21.2	1.77	1.77	98.23
2.36mm	99.0	8.25	10.02	89.98
1.18mm	444.9	37.08	47.10	52.90
600µm	383.9	31.99	79.09	20.91
425µm	92.4	7.7	86.79	13.21
300µm	63.5	5.29	92.08	7.92
212µm	44.3	3.69	95.77	4.23
150µm	18.7	1.56	97.33	2.67
75µm	13.9	1.16	98.49	1.51
Pan	5.2	0.43	98.92	1.08

Table 4.1 presented the results of the sieve analysis carried out on fine aggregate (sand) using a total test sample weight of 1200 g. The test was conducted to determine the particle size distribution of the aggregate. From the table, it was observed that no material was retained on the 10 mmsieve, indicating that all the particles were smaller than 10 mm in size. A small amount of material (21.2 g or 1.77%) was retained on the 5 mm sieve, while 99.0 g (8.25%) was retained on the 2.36 mm sieve. The largest proportion of the aggregate was retained on the 1.18 mm sieve, with 444.9 g representing 37.08% of the total sample. This indicated that most of the particles were concentrated around this sieve size. A significant amount of material (383.9 g or 31.99%) was also retained on the 600 μm sieve, bringing the cumulative retained percentage to 79.09%. As the sieve size decreased further, the amount of material retained also decreased gradually. 92.4 g (7.70%) was retained on the 425 μm sieve, while smaller amounts were retained on the 300 μm, 212 μm, 150 μm, and 75 μm sieves. Only 5.2 g (0.43%) of the sample passed through all the sieves and was collected in the pan, indicating that the proportion of very fine particles in the aggregate was minimal. Overall, the results showed that the aggregate had a well-distributed range of particle sizes, with most particles falling between 1.18 mm and 600 μm.

Table 4.2 shows the sieveanalysis for coarse aggregate (Granite), while figure 4.1 represents the particle size distribution of both fine and coarse aggregate samples.

Table 4.2: Sieve Analysis for Coarse Aggregate (Granite)

WEIGHT OF TEST SAMPLE = 5000g				
BS Sieve Size(mm)	**Weight Retained(g)**	**Percentage Retained (%)**	**Cumulative Retained (%)**	**Percentage Passing (%)**
37.5mm	0.00	0.00	0.00	100.00
25mm	494.8	9.90	9.90	90.1
19mm	1066.4	21.33	31.23	68.77
14mm	2483.1	49.66	80.89	19.11
10mm	576.3	11.53	92.42	7.58
5mm	195.7	3.91	96.33	3.67
2.36mm	33.6	0.67	97.00	3.00
Pan	122.2	2.44	99.44	0.56

Table 4.2 presents the sieve analysis results of the coarse aggregate (granite) based on a 5000 g sample. The results indicate that no particles were retained on the 37.5 mm sieve, confirming that the maximum aggregate size is less than 37.5 mm. A substantial proportion of the aggregate (49.66%) was retained on the 14 mm sieve, while 21.33% and 9.90% were retained on the 19 mm and 25 mm sieves respectively, indicating that the aggregate is predominantly within the 14–19 mm size range.

This gradation trend is consistent with findings reported by Neville A. M., who noted that well-graded coarse aggregates for structural concrete typically exhibit a concentration of particle sizes within intermediate sieve ranges, ensuring adequate packing density and reduced void content. Similarly, Shetty M. S. observed that aggregates with a dominant size fraction between 10 mm and 20 mm contribute to improved workability and strength characteristics due to better inter-particle interlocking.

The minimal percentage of fines (0.56% passing the 2.36 mm sieve) aligns with the recommendations of British Standards Institution in BS 882, which specifies that excessive fines in coarse aggregates can adversely affect concrete strength and durability. The observed low fines content therefore indicates good aggregate cleanliness and suitability for structural applications.

Furthermore, the overall gradation suggests a well-distributed particle size composition, which is in agreement with the provisions of British Standards Institution in BS 1377-2:1990, where well-graded aggregates are characterized by a smooth distribution curve with minimal gaps in particle sizes. Such gradation enhances compaction, reduces permeability, and improves the mechanical performance of concrete. The results are also consistent with the work of Oyelade, *et al*., 2024, who reported that granite aggregates with similar gradation (dominant 12–20 mm fraction and low fines content) exhibited high compressive strength and durability performance in concrete mixes.

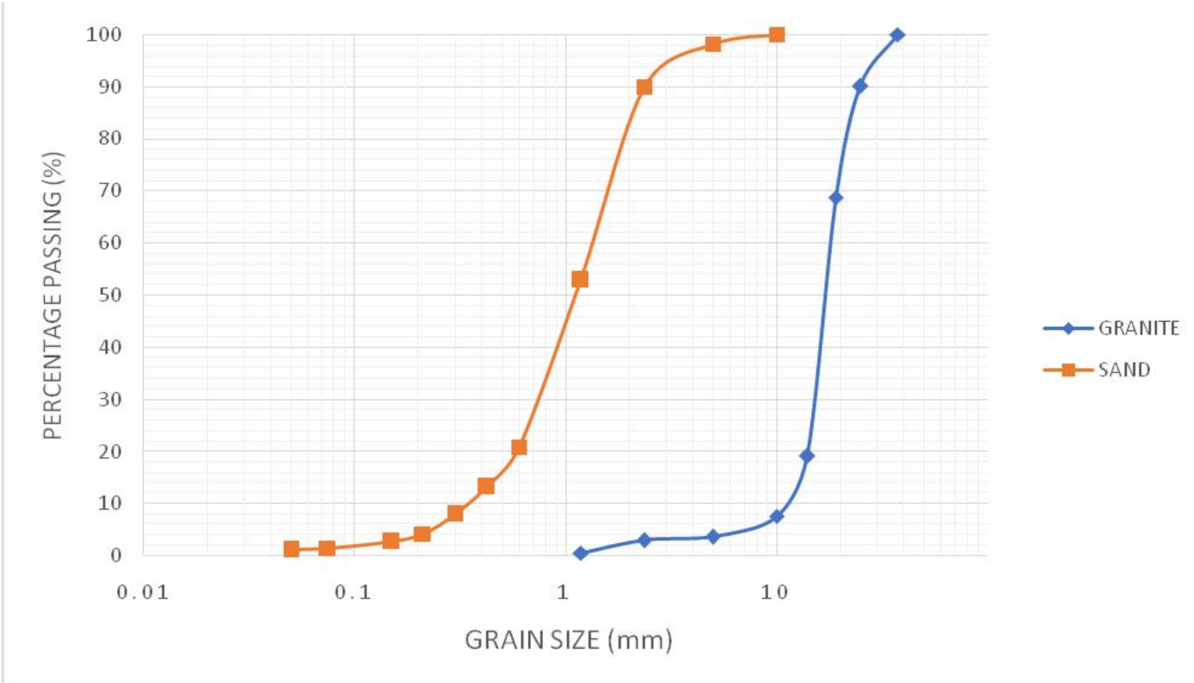

Figure 4.1 presents the particle size distribution curves for both fine and coarse aggregates. The fine aggregate (sand) exhibited a uniformity coefficient (Cu) of 3.33 and a coefficient of curvature (Cc) of 1.30, while the coarse aggregate (granite) showed Cu = 1.73 and Cc = 1.07. Additionally, 96.33% of the coarse aggregate was retained on the 5 mm sieve, with only 3.67% passing, indicating a predominance of larger particle sizes.

According to the criteria outlined in ASTM International D2487 (Unified Soil Classification System), well-graded sands typically have $Cu \geq 6$ and $1 \leq Cc \leq 3$. The obtained values for sand (Cu = 3.33, Cc = 1.30) therefore indicate that the material is poorly graded (uniform or gap-graded) rather than well-graded. This observation is consistent with the classification of the sand as gap-graded medium to coarse sand, suggesting a deficiency in intermediate particle sizes. This finding aligns with the work of Das B. M.,who reported that sands with Cu values less than 6 generally exhibit uniform grading, which can lead to reduced packing efficiency and higher void ratios compared to well-graded sands. Similarly, Bowles J. E.

noted that poorly graded sands often require careful mix proportioning in concrete to avoid segregation and excessive cement demand.

For the coarse aggregate, the values obtained ($Cu = 1.73$, $Cc = 1.07$) further confirm a poorly graded or nearly uniform material, as well-graded gravels typically require $Cu \geq 4$ and $1 \leq Cc \leq 3$. The narrow range of particle sizes is also supported by the high percentage (96.33%) retained on the 5 mm sieve, indicating a concentration of particles within a limited size band.

These results are comparable to findings by Neville A. M., who emphasized that gap-graded or uniformly graded coarse aggregates may lead to reduced interlocking and increased void content, although they can sometimes improve workability when properly proportioned. In contrast, well-graded aggregates generally enhance density, strength, and durability due to improved particle packing.

Table 4.3: Grading coefficients

Aggregates	Coefficient of uniformity	Coefficient of curvature
Sand	3.33	1.30
Granite	1.73	1.07

Table 4.3 presents the grading coefficients for the aggregate particle size distribution, specifically the Coefficient of Uniformity (Cu) and Coefficient of Curvature (Cc).

4.1.2 Moisture Content Test

The moisture content test was carried out to determine the amount of water present in the materials used in this project. The results obtained are as shown thus:

Moisture Content (%) of sand is0.73% and granite is24.7g

4.1.3 Dry Density and Bulk Density Test

Density values obtained from equation 3.2

Bulk density	Sand	1331.57kg/m^3
	granite	1376.84kg/m^3
Dry density	Sand	769.69kg/m^3
	granite	844.68kg/m^3

4.1.4 Aggregate Crushing Value

Percentage fines = $\frac{W_1}{W_2} \times 100$ from equation 3.4

Aggregate Crushing Value (ACV)	29.79%

4.1.5 Aggregate Impact Value

Percentage fines = $\frac{W_1}{W_2} \times 100$ from equation 3.4

Aggregate Impact Value (AIV)	20 %

The following is a summary of the physical properties of the materials used as shown in Table 4.4.

Table 4.4: Physical properties of aggregates

Physical Property	**Sand**	**Granite**
Specify Gravity	2.63	2.66
Uniformity Coefficient (Cu)	3.33	1.73
Coefficient of Curvature (Cc)	1.3	1.07
Moisture Content (%)	0.73	0.63
Bulk Density (Kg/m^3)	1331.57	1376.84
Dry Density (Kg/m^3)	769.69	844.64
Aggregate Crushing Value (%)	-	29.79
Aggregate Impact Value (%)	-	20

The specific gravity values obtained for the sand (2.63) and granite (2.66) fall within the typical range of natural aggregates (2.4–2.9). This is consistent with the findings of Neville A. M., who reported that most normal weight aggregates used in structural concrete generally have specific gravities between 2.5 and 2.7. The similarity between the two values also suggests uniform mineral composition and confirms the suitability of the materials for concrete production.The bulk density of the fine aggregate and coarse aggregate were recorded as 1331.57 kg/m^3 and 1376.84 kg/m^3, respectively. Both values were observed to fall within the range of 1200–1750 kg/m^3, which has been identified in the literature as the typical bulk density of aggregates used in the production of normal-weight concrete, as standardised by ASTM C29 (Neville, 2011; ASTM, 2017). It has further been reported that in normal concrete, aggregate bulk density generally ranges between 1520 and 1680 kg/m^3, with values below this range still being considered acceptable for normal-weight concrete applications (Mehta & Monteiro, 2014). The dry density values recorded for sand (769.69 kg/m³) and granite (844.64 kg/m³) indicate that granite is denser than sand, with the sand being approximately 4.27% lighter. This observation aligns with the work of Das B. M., who stated that coarse aggregates typically exhibit higher dry densities than fine aggregates due to reduced void ratios and better particle interlocking.The moisture content of the fine aggregate and coarse aggregate were determined to be 0.73% and 0.63%, respectively. The relatively higher moisture content recorded in the fine aggregate has been attributed to the smaller particle size of sand, which provides a greater surface area for water retention. It has been established in previious literature that the moisture content of aggregates can range from less than 1% in gravel to as high as 40% in very porous materials (Neville, 2011). Furthermore, it has been recommended that the moisture content of fine aggregates should not exceed 5%, while that of coarse aggregates should not exceed 2%, beyond which moisture correction is required in concrete mix design (American Concrete Institute [ACI], 2016).The Aggregate Crushing Value (ACV) of 29.79% for granite falls within the acceptable range for coarse aggregates used in concrete. According to British Standards Institution (BS 812), aggregates with ACV values below 30% are considered suitable for structural concrete. This result is comparable to the findings of Neville A. M., who emphasized that lower ACV values indicate higher resistance to crushing and better load-bearing capacity.The aggregate impact value of the granite was found to be 20%. It has been reported that higher-strength concrete aggregates typically exhibit aggregate impact values of less than 20%, while very few aggregates produce values below 10% (BSI, 1990b). The value obtained in this study was observed to be at the boundary of what is considered characteristic of higher-strength aggregate, indicating that the granite possesses adequate toughness for use in concrete.

4.2 Workability

Workability of concrete is a composite property of fresh concrete and it includes diverse requirements of mixability, stability, transportability, placeability, mobility, compatibility, and finishability. The concrete slump test is an empirical test that measures the workability of fresh concrete. More specifically, it measures the consistency of the concrete in that specific batch. This test is performed to check the consistency of freshly made concrete. Consistency is a term very closely related to workability. It is a term which describes the state of fresh concrete. It refers to the ease with which the concrete flows. It is used to indicate the degree of wetness. Workability of concrete is mainly affected by consistency i.e. wetter mixes will be more workable than drier mixes, but concrete of the same consistency may vary in workability. It is also used to determine consistency between individual batches. The test is popular due to the simplicity of apparatus used and simple procedure. Table 4.5 presents the slump test results, conducted according to BS 5328 (section 7.2), evaluating the workability of fresh concrete with various mix proportions at a water-cement ratio of 0.55.

Table 4.5: Slump values and degree of workability

Percentage Volume Steel Fibre	Slump Value	Degree of Workability
0%	67	Medium
2.5%	61	Medium
5%	53	Medium
7.5%	47	Low
10%	41	Low

The effect of steel fibre content on the workability of concrete, as measured by slump, is presented in Table 4.5. A slump of 67 mm was recorded for the control mix (0% steel fibre), which was classified as medium workability and considered suitable for standard casting operations. Upon the incorporation of 2.5% steel fibre, a slight reduction in slump to 61 mm was observed, though the mix was retained within the medium workability classification. At a fibre content of 5%, the slump was further reduced to 53 mm; the mix was still classified as medium workability, although a noticeable increase in stiffness was observed. At fibre contents of 7.5% and 10%, marked reductions in slump to 47 mm and 41 mm were respectively recorded, resulting in mixes categorised as low workability (see Figure 4.2).

A consistent trend of decreasing slump with increasing steel fibre content was identified throughout the investigation. This observation is consistent with findings reported by Figueiredo and Ceccato (2015) the fibres act as a barrier to coarse aggregate movement, thereby reducing the material's overall mobility. Adisa *et al*., 2026 and Hassan and Saeed, 2024 also reported a progressive slump reduction attributed to increased internal friction and fibre interlocking within the fresh concrete matrix.

Therefore, higher fibre contents may require adjustments in water content or the use of superplasticizers to maintain proper workability during mixing and casting.

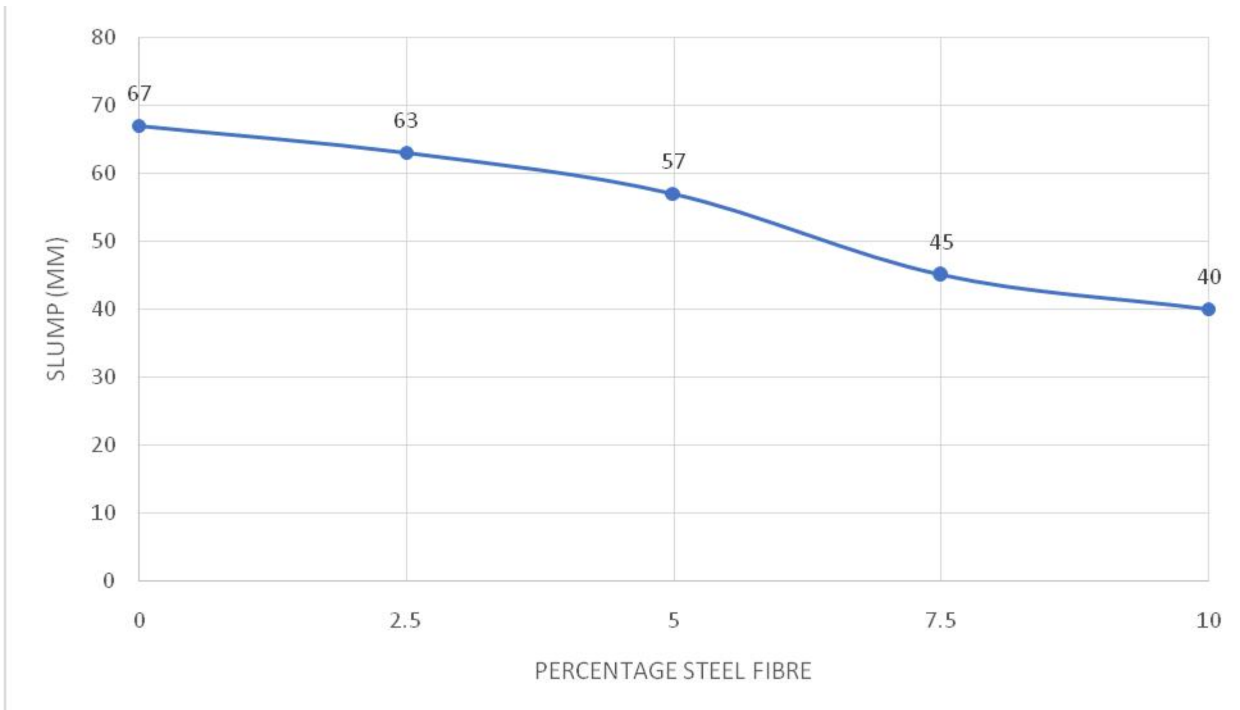

Figure 4.1: Variation of workability with increasing steel fibre content

It was observed that the workability decreased from 67 mm to 40 mm as the percentage volume of steel fibre increased from 0% to 10% steel fibre. The result of the slump test showed that all of the mixes have medium degree of workability except the 7.5% and 10%. The slump decreased by 5.97% from 0% to 2.5%. This value is 9.52%, 21.05% and 11.11% for the 5%, 7.5% and 10% volume respectively. On an average there is a 11.91% decrease in slump per 2.5% increase in percentage steel fibre.

4.3 Compressive strengths of steel fibre reinforced concrete

Compressive strength has been found out at the ages 7, 14, 21and 28 days after moist curing the specimens continuously. Three cubes each were cast for each curing age at water cement ratios of 0.55. The test results are presented in Table 4.6.

Table 4.6: Compressive strength values for concrete cubes (0% Steel fibres)

Days	Weight of Specimen (kg)	Force (KN)	Compressive Strength (N/mm^2)	Average Compressive Strength (N/mm^2)
7 days	8.85	375	16.67	15.56
	9.14	330	14.67	
	8.86	345	15.33	
14 days	8.74	410	18.22	17.85
	8.97	400	17.78	
	9.22	395	17.56	
21 days	8.72	475	21.11	20.89
	8.74	490	21.78	
	8.52	445	19.78	
28 days	8.83	555	24.67	24.44
	8.46	525	23.33	
	8.70	570	25.33	

Table 4.6 presents the compressive strength development of concrete cubes without steel fibres at curing ages of 7, 14, 21, and 28 days. The results show a steady increase in strength

from an average of 15.56 N/mm² at 7 days to 24.44 N/mm² at 28 days, reflecting the normal progression of cement hydration. The 7-day strength represents approximately 64% of the 28-day strength, which is consistent with the observations of Neville, 2011, who reported that conventional Portland cement concrete typically achieves about 60–70% of its 28-day strength within the first 7 days under normal curing conditions. This confirms that the concrete exhibited normal early strength development. At 14 days, the average strength increased to 17.85 N/mm², representing about 73% of the 28-day strength. This trend aligns with findings by Shetty M. S., who noted that strength gain between 7 and 14 days is usually significant due to ongoing hydration of cement compounds, particularly tricalcium silicate (C_3S).The continued increase in strength at 21 days (average of 20.89 N/mm²) further supports the typical hydration pattern described by Mehta and Monteiro, 2014 who explained that later-age strength gain is primarily governed by the slower hydration of dicalcium silicate (C_2S), contributing to long-term strength development.By 28 days, the concrete achieved an average compressive strength of 24.44 N/mm², which falls within the expected range for normal-strength concrete. According to British Standards Institution, characteristic compressive strengths for conventional structural concrete typically range from 20 to 30 N/mm², depending on mix design and exposure conditions.

Table 4.7- 4.10 show the percentage steel fibre from 2.5% - 10% respectively at different curing ages of 7, 14, 21, and 28 days.

Table 4.7 at 2.5% Steel Fibres

Days	Weight of Specimen (kg)	Force (kN)	Compressive Strength (N/mm²)	Average Compressive Strength (N/mm²)
7 days	8.77	370	16.44	17.48
	8.37	410	18.22	
	8.33	400	17.78	
14 days	8.86	445	19.78	21.48
	8.64	510	22.67	
	8.79	495	22	
21 days	8.78	580	25.78	24.08
	8.41	515	22.89	
	8.76	530	23.56	
28 days	8.68	590	26.22	26.74
	8.76	640	28.44	
	8.8	575	25.56	

For each curing age, three concrete specimens were tested to determine the compressive strength. The table includes the weight of the specimen, applied force (kN), compressive strength (N/mm²), and the average compressive strength for each curing period. At 7 days, the compressive strengths recorded were 16.44 N/mm², 18.22 N/mm², and 17.78 N/mm², giving an average compressive strength of 17.48 N/mm². This shows the early strength development of the concrete after one week of curing. At 14 days, the compressive strength increased to 19.78 N/mm^2, 22.67 N/mm^2, and 22.00 N/mm^2, with an average value of 21.48 N/mm^2. This increase indicates continued hydration of cement and improvement in the bonding between the steel fibres and the concrete matrix. At 21 days, the compressive strength values were 25.78 N/mm^2, 22.89 N/mm^2, and 23.56 N/mm^2, producing an average compressive strength of 24.08 N/mm^2. This shows a further improvement in strength as curing progresses. At 28 days, which is the standard age for evaluating concrete strength, the values recorded were 26.22 N/mm^2, 28.44 N/mm^2, and 25.56 N/mm^2, with an average compressive strength of 26.74 N/mm^2. This represents the highest compressive strength obtained, indicating that the concrete gained strength with increasing curing time.

Table 4.8 at 5% Steel Fibres

Days	Weight of Specimen (kg)	Force (kN)	Compressive Strength (N/mm^2)	Average Compressive Strength (N/mm^2)
7 days	8.69	415	18.44	19.18
	8.49	435	19.33	
	8.34	445	19.78	
14 days	8.62	470	20.89	22.37
	8.53	500	22.22	
	8.63	540	24	
21 days	8.64	585	26	25.18
	8.61	565	25.11	
	8.38	550	24.44	
28 days	8.38	695	30.89	30.15
	8.18	700	31.11	
	8.42	640	28.44	

At the earliest stage, 7 days, the average compressive strength stands at 19.18 N/mm^2. As the curing progresses to 14 days, this value increases to 22.37 N/mm^2 and further to 25.18 N/mm^2 at 21 days. The most significant gains are typically seen as the concrete approaches its design life, with the average compressive strength reaching 30.15 N/mm^2 after 28 days. This trend is consistent with the hydration process of cement, where the formation of calcium silicate hydrates continues, gradually increasing the material's stiffness and strength.

The presence of steel fibers likely contributes to this strength development by bridging micro cracks that may form during hydration and by improving the overall composite action.

Table 4.9 at 7.5% Steel fibres

Days	Weight of Specimen (kg)	Force (kN)	Compressive Strength (N/mm²)	Average Compressive Strength (N/mm²)
7 days	8.66	470	20.89	22.07
	8.46	540	24	
	8.32	480	21.33	
14 days	8.58	575	25.56	25.93
	8.5	635	28.22	
	8.6	540	24	
21 days	8.6	675	30	29.26
	8.6	655	29.11	
	8.37	645	28.67	
28 days	8.34	795	35.33	32.3
	8.18	715	31.78	
	8.42	670	29.78	

These tests were performed at regular intervals, specifically after 7, 14, 21, and 28 days of curing. For each designated curing period, three distinct concrete cubes were subjected to compression testing. The Average Compressive Strength (N/mm²), which represents the mean strength of the three tested specimens. A notable trend evident from the table is the progressive increase in the average compressive strength of the concrete as it undergoes longer curing periods. For instance, the concrete exhibits an average strength of 22.07 N/mm² at 7 days, which then ascends to 32.3 N/mm² by the 28-day mark. This consistent gain in strength over time underscores the importance of the curing process for concrete development, with the inclusion of 7.5% steel fibers playing a role in the material's mechanical performance.

Table 4.10 at 10% Steel fibres

Days	Weight of Specimen (kg)	Force (kN)	Compressive Strength (N/mm^2)	Average Compressive Strength (N/mm^2)
7 days	8.7	570	25.33	25.85
	8.32	580	25.78	
	8.25	595	26.44	
14 days	8.82	640	28.44	27.55
	8.59	610	27.11	
	8.7	610	27.11	
21 days	8.69	765	34	32.52
	8.33	705	31.33	
	8.68	725	32.22	
28 days	8.63	835	37.11	36.81
	8.21	865	38.44	
	8.73	785	34.89	

The table documents the strength development of concrete cubes at 7, 14, 21, and 28 days of curing. The average compressive strength as the curing period extends, at 7 days; the average strength is recorded as 25.85 N/mm². This value escalates to 27.55 N/mm² at 14 days, further rises to 32.52 N/mm² at 21 days, and culminates at a notable 36.81 N/mm² after 28 days of curing. This progression clearly illustrates the ongoing maturation and strengthening of the concrete, a process influenced by the incorporated 10% steel fibers and the established water-cement ratio of 0.55.

Figure 4.3 illustrates the relationship between compressive strength (N/mm²) and varying percentages of steel fiber content, while Figure 4.4 shows the variation of compressive strength (N/mm2) with curing age.

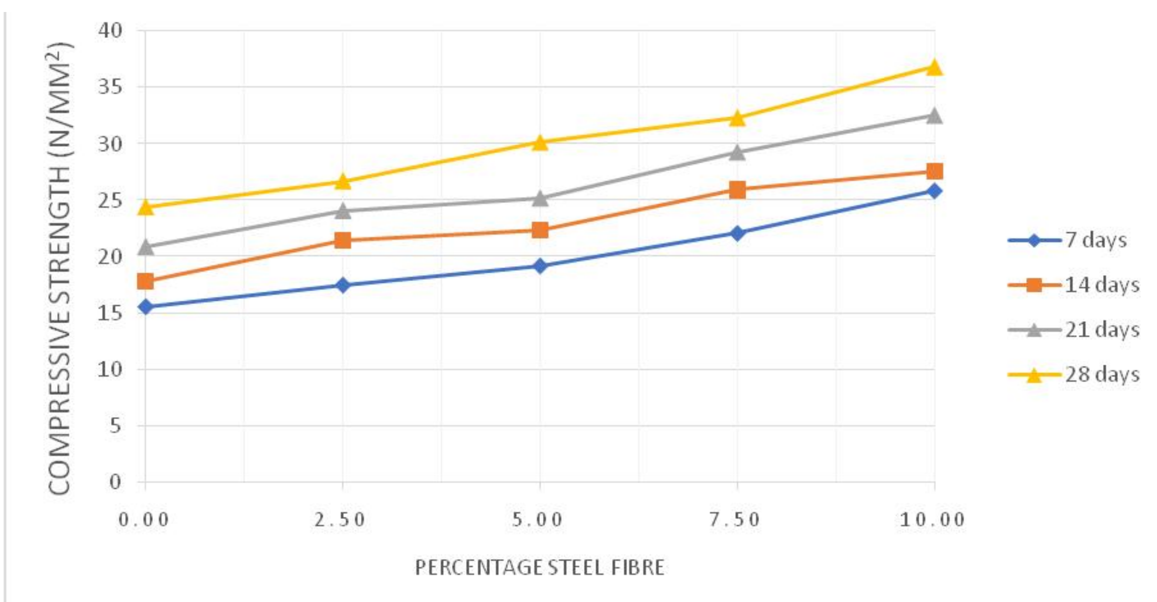

Figure 4.2:Variation of Compressive Strength (N/mm^2) with percentage steel fibre

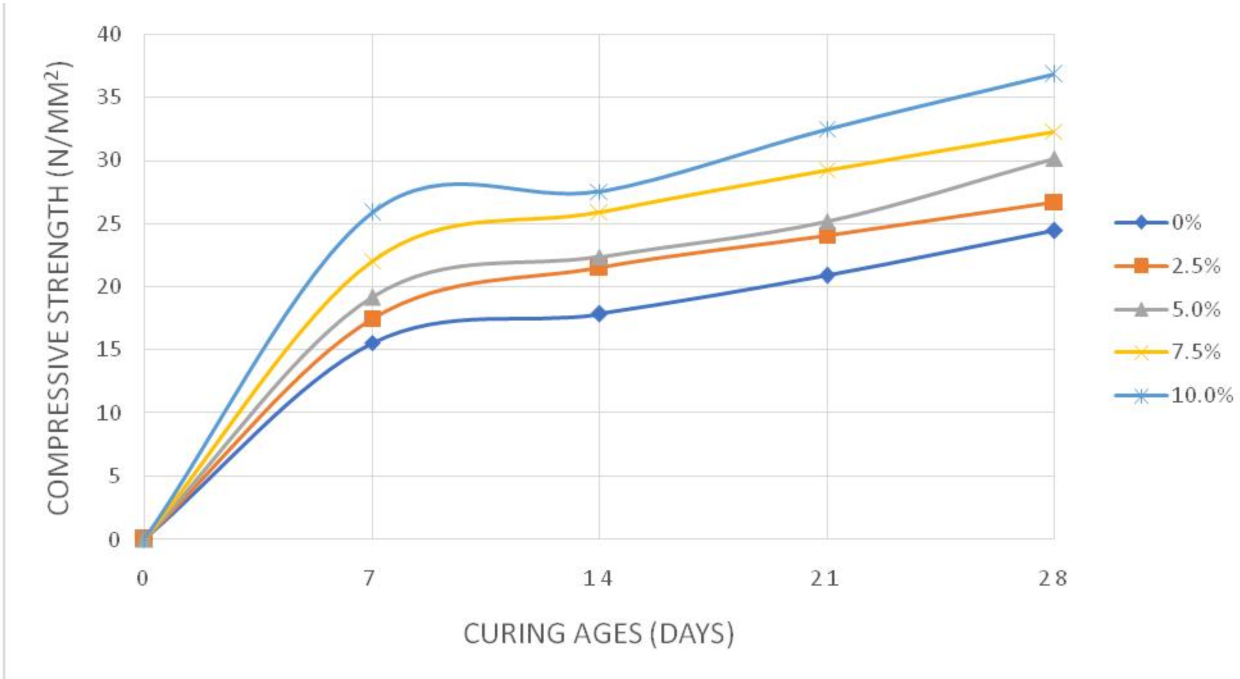

Figure 4.3: Variation of Compressive Strength (N/mm^2) with Curing Age

i. From Tables 4.7 – 4.10 and Figure 4.3, it was observed that compressive strength of concrete increases with increase in percentage steel fiber. This is an indication that increasing the percentage steel fibre content of any concrete will increase its compressive strength. This is also in accordance of the findings of Avinash (2016) and Sashk (2018).

ii. From Figure 4.4, the strength values increased as the curing ages increase progressively. This shows the effect of water in the development of strength in normal concrete. It is further observed that the strength development pattern was relatively similar for all the concrete specimens, irrespective of the percentage steel fibre. It was observed that there is a variation of increment in the compressive strength.

iii. It was further observed that the 28-day strengths of most specimens were all reasonably above 25 N/mm^2. Hence most the concrete mix used for the experiment is above M25 concrete grade.

iv. It was also observed that none of the specimens have strength above 40 N/mm^2, hence they can't be classified as high strength concrete.

4.4 Tensile Strength of Concrete Cylinder

The tensile strength is one of the basic and important properties of the concrete. Cylinders of size 150mm in diameter and 300mm height were cast for split tensile test. The splitting tests are well known as indirect tests used for determining the tensile strength of concrete. Tensile strength has been found out at the ages 7, 14, 21 and 28 days after moist curing the specimens continuously. Two cylinders each were cast for each curing age at percentage steel fibre of 0% to 10% in steps of 2.5%. The test results are presented in table 4.12.

Table 4.11: Tensile strength values of concrete cylinders (at 0 % Steel Fibres)

Days	Weight of Specimen (kg)	Force (kN)	Tensile Strength (N/mm^2)	Average Tensile Strength (N/mm^2)
7 days	12.65	150	2.12	2.26
	12.33	170	2.4	
14 days	12.48	190	2.69	2.87
	12.55	215	3.04	
21 days	12.42	220	3.11	3.25
	11.95	240	3.39	
28 days	12.42	250	3.54	3.54
	12.36	250	3.54	

Table 4.11 provides a detailed breakdown of the tensile strength test results for concrete cubes that contain no steel fibers (0% steel fiber). The experiments were conducted at four distinct curing ages: 7, 14, 21, and 28 days. At 7 days, the average tensile strength is recorded as 2.26 N/mm². This value sees a gradual rise to 2.87 N/mm² at 14 days, further climbing to 3.25 N/mm² at 21 days. By the 28-day mark, the average tensile strength reaches its highest point in this series, standing at 3.54 N/mm². At 28 days, both tested cubes registered an identical tensile strength of 3.54 N/mm², matching their average. This consistency, along with the steady increase in strength across the curing periods, reinforces the reliability of the observed data and confirms the behavior of concrete gaining tensile capacity as it cures.

Table 4.12 presents the results of tensile strength tests conducted on concrete cubes that contain 2.5 steel fibers, serving as a control group in the experiment.

Table 4.12 at 2.5% Steel fibres

Days	Weight of Specimen (kg)	Force (kN)	Tensile Strength (N/mm²)	Average Tensile Strength (N/mm²)
7 days	12.62	190	2.69	2.76
	12.08	200	2.83	
14 days	11.96	195	2.76	2.9
	12.78	215	3.04	
21 days	12.46	245	3.47	3.51
	12.65	250	3.54	
28 days	12.65	270	3.82	4.03
	12.14	300	4.24	

The tests were performed at four different curing ages: 7, 14, 21, and 28 days. At the 7-day, the average tensile strength is 2.76 N/mm². This value experiences a steady ascent, reaching 2.9 N/mm² at 14 days, further increasing to 3.51 N/mm² at 21 days. The highest average tensile strength for this group is observed at 28 days of curing, where it measures 4.03 N/mm². This progressive improvement in tensile strength underscores the ongoing development of the concrete's internal structure through hydration and cementations reactions over time. The final average tensile strength of 4.03 N/mm² at 28 days represents the concrete's fully developed strength in tension under these specific laboratory conditions, free from the influence of steel fiber reinforcement.

Table 4.13 discusses the tensile strength performance of concrete specimens that have been reinforced with 5% steel fibers, assessed across various curing durations.

Table 4.14at 5% steel fibres

Days	Weight of Specimen (kg)	Force (kN)	Tensile Strength (N/mm²)	Average Tensile Strength (N/mm²)
7 days	12.67	185	2.62	2.83
	13.01	215	3.04	
14 days	12.66	225	3.18	3.29
	12.48	240	3.39	
21 days	12.82	260	3.68	3.65
	13.16	255	3.61	
28 days	12.44	290	4.1	4.25
	12.53	310	4.39	

The table spans four distinct curing periods: 7, 14, 21, and 28 days. At the initial 7-day testing interval, the average tensile strength recorded is 2.83 N/mm². This value demonstrates a notable increase to 3.29 N/mm² by the 14-day mark. The upward trend continues, with the average tensile strength reaching 3.65 N/mm² at 21 days. The highest average tensile strength for this group is observed at the 28-day mark, achieving a value of 4.25 N/mm².

Table 4.14 provides a detailed breakdown of the tensile strength test results for concrete cubes incorporating 7.5% steel fibers, examined at sequential curing intervals of 7, 14, 21, and 28 days, all prepared with a consistent water-cement ratio of 0.55.

Table 4.14 at 7.5% Steel Fibres

Days	Weight of Specimen (kg)	Force (kN)	Tensile Strength (N/mm^2)	Average Tensile Strength (N/mm^2)
7 days	12.72	200	2.83	3.11
	12.39	240	3.39	
14 days	12.56	240	3.39	3.43
	12.54	245	3.47	
21 days	12.02	250	3.54	3.68
	12.53	270	3.82	
28 days	12.45	295	4.17	4.28
	11.84	310	4.39	

Beginning at 7 days of curing, the average tensile strength is recorded as 3.11 N/mm^2. This figure shows a steady increase over time, rising to 3.43 N/mm^2 at 14 days and further to 3.68 N/mm^2 at 21 days. The progression culminates at the 28-day curing stage, where the concrete achieves its highest average tensile strength within this experimental set, measuring 4.28 N/mm^2. This consistent upward trend highlights the ongoing development and strengthening of the concrete matrix, enhanced by the presence of steel fibers which effectively contribute to the material's resistance to tensile stress as it cures and gains internal cohesion.

Table 4.15 shows the tensile strength tests conducted on concrete specimens reinforced with 10% steel fibers, evaluated across four distinct curing periods: 7, 14, 21, and 28 days with water-cement ratio of 0.55.

Table 4.15 at 10% Steel fibres

Days	Weight of Specimen (kg)	Force (kN)	Tensile Strength (N/mm^2)	Average Tensile Strength (N/mm^2)
7 days	12.32	225	3.18	3.43
	12.38	260	3.68	
14 days	12.26	240	3.39	3.5
	11.81	255	3.61	
21 days	12.24	285	4.03	4.14
	12.18	300	4.24	
28 days	12.08	305	4.31	4.56
	12.03	340	4.81	

At the initial 7-day testing phase, the average tensile strength observed is 3.43 N/mm². This value sees a substantial rise to an average of 3.5 N/mm² by the 14-day mark. The progression continues, with the average tensile strength reaching 4.14 N/mm² at 21 days. The highest average tensile strength for this set of tests is recorded at 28 days, attaining a value of 4.56 N/mm². This progressive enhancement signifies the beneficial impact of the steel fibers in conjunction with the maturing concrete matrix, where the fibers play a crucial role in load distribution and crack propagation resistance as the concrete gains strength over time.

Table 4.16 provides a comprehensive analysis of the tensile strengths exhibited by concrete cylinders incorporating varying percentages of steel fibers, examined at multiple curing ages.

Figure 4.5 illustrates the relationship between tensile strength (N/mm²) and varying percentages of steel fiber content. The variation in tensile strength with different curing age is presented in Figure 4.6

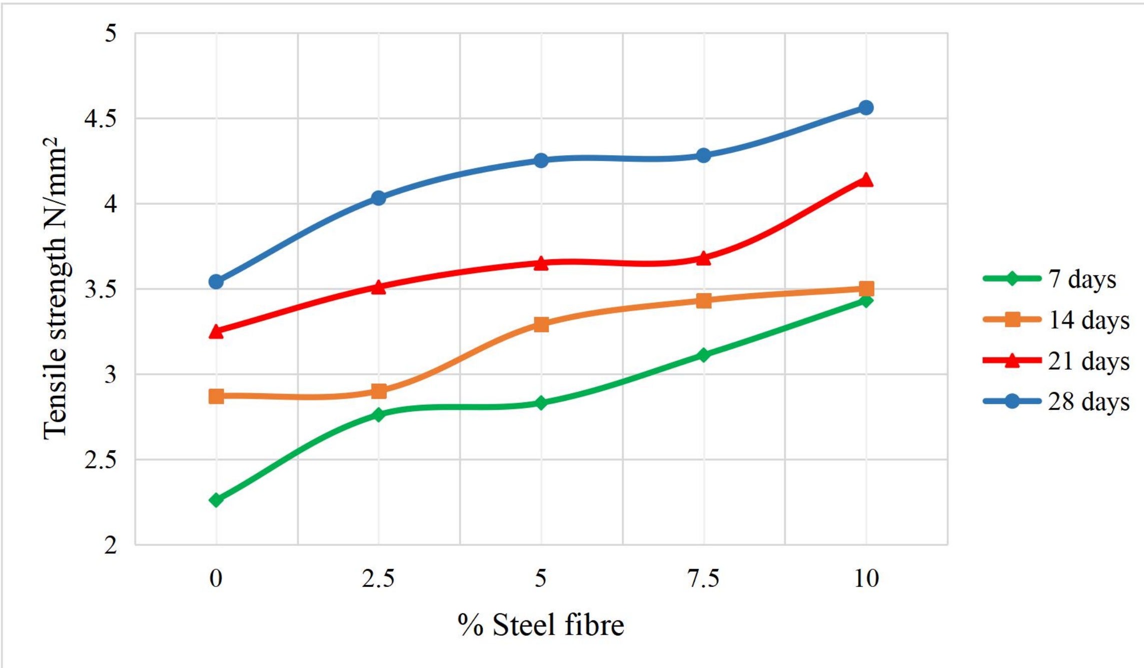

Figure 4.4: Variation of Tensile Strength (N/mm²) with percentage steel fibre

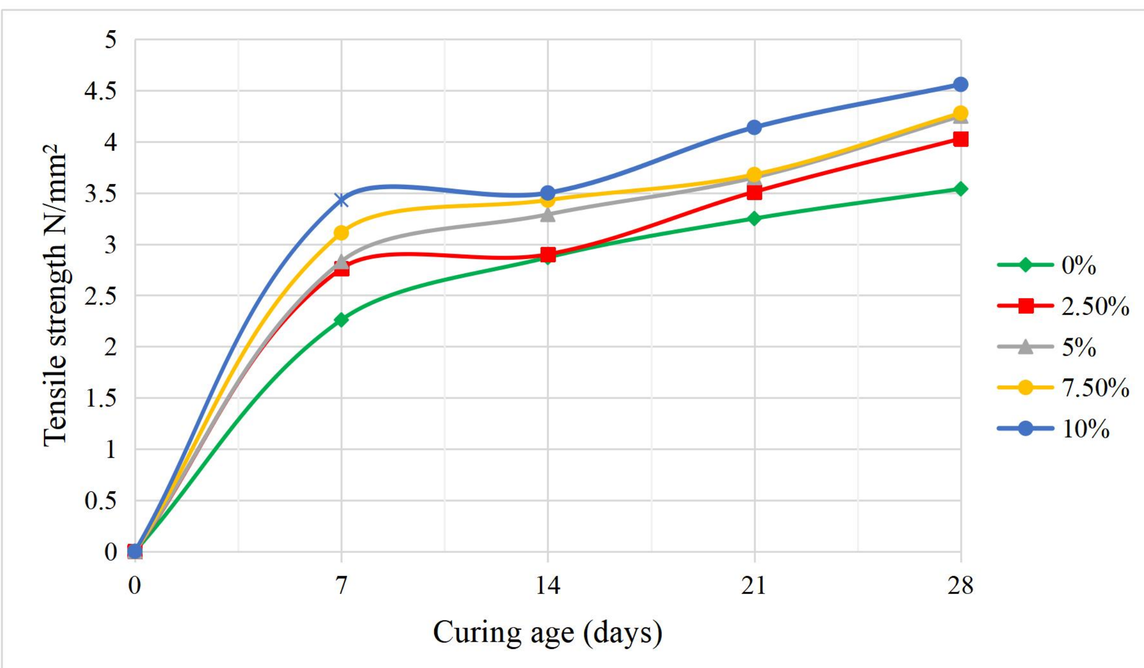

Figure 4.5: Variation of Tensile Strength (N/mm^2) with curing age

i. From figure 4.5, it was observed that tensile strength of concrete increases with increase in percentage steel fiber. This is an indication that increasing the percentage steel fibre content of any concrete will increase its compressive strength. This is also in accordance of the findings of Avinash (2016) and Sashki (2018).

ii. From Fig 4.6, the strength values increased as the curing ages increase progressively. This shows the effect of water in the development of strength in normal concrete. It is further observed that the strength development pattern was relatively similar for all the concrete specimens, irrespective of the water cement ratio. It was observed that there is a variation of increment in the compressive strength.

iii. It was further observed that the 28-day strengths of all specimens were all reasonably above 3 N/mm^2.

4.5 Flexural Strength of Concrete Beams

Table 4.18 presents the flexural strength values of concrete beams that do not contain any steel fibers, thus serving as a baseline for comparison.

Table 4.18: Flexural strength values of concrete beams (at 0% Steel fibres)

Days	Weight of Specimen (kg)	Force (kN)	Flexural Strength (N/mm^2)	Average Flexural Strength (N/mm^2)
7 days	38.28	13	4.33	4.67
	36.69	15	5.00	
28 days	37.23	20	6.67	6.5
	38.88	19	6.33	

The table shown the results obtained from tests conducted at two distinct curing ages: 7 days and 28 days. At the 7-day testing interval, the flexural strengths recorded are 4.33 N/mm² and 5.00 N/mm², resulting in an average flexural strength of 4.67 N/mm². This indicates a developing capacity to resist bending stresses in the early stages of curing. By the 28-day mark, the concrete exhibits significantly improved flexural performance. The individual strengths measured are 6.67 N/mm² and 6.33 N/mm², leading to a higher average flexural strength of 6.5 N/mm². The progression from 4.67 N/mm² at 7 days to 6.5 N/mm² at 28 days highlights the substantial strength gain experienced by concrete during its curing process.

Table 4.19 presents the flexural strength values of concrete beams that do not contain any steel fibers, thus serving as a baseline for comparison.

Table 4.19 at 2.5% Steel Fibres

Days	Weight of Specimen (kg)	Force (kN)	Flexural Strength (N/mm^2)	Average Flexural Strength (N/mm^2)
7 days	36.73	14	4.67	4.83
	37.09	15	5.00	
28 days	36.68	21	7.00	7
	37.23	21	7.00	

The compressive strength of concrete was evaluated at various curing ages, specifically 7, and 28 days, with continuous moist curing. Three identical cube specimens were prepared and tested for each curing age, all with a consistent water-cement ratio of 0.55. The comprehensive test results are detailed in Table 4.19, providing insights into the strength development of the concrete over time. At the 7-day testing interval, the flexural strengths recorded are 4.67 N/mm² and 5.00 N/mm², resulting in an average flexural strength of 4.83 N/mm². By the 28-day mark, the concrete exhibits significantly improved flexural performance. The individual strengths measured are 7.0 N/mm² and 7.0 N/mm², leading to a higher average flexural strength of 7.0 N/mm².

Table 4.20 summarizes the flexural strength results for concrete cubes with 5% steel fibers, tested at 7, and 28 days.

Table 4.20: at 5% Steel Fibres

Days	Weight of Specimen (kg)	Force (kN)	Flexural Strength (N/mm^2)	Average Flexural Strength (N/mm^2)
7 days	37.77	15	5.00	5.17
	38.68	16	5.33	
28 days	39.67	21	7.00	7.17
	36.94	22	7.33	

The comprehensive test results show the details strength development of the concrete over time. At the 7-day testing interval, the flexural strengths recorded are 5.0 N/mm² and 5.33 N/mm², resulting in an average flexural strength of 5.17 N/mm². By the 28-day mark, the concrete exhibits significantly improved flexural performance. The individual strengths measured are 7.0 N/mm² and 7.33 N/mm², leading to a higher average flexural strength of 7.17N/mm².

Table 4.21 presents the flexural strength results of concrete beams that have been reinforced with 7.5% steel fibers.

Table 4.21: at 7.5% Steel Fibres

Days	Weight of Specimen (kg)	Force (kN)	Flexural Strength (N/mm^2)	Average Flexural Strength (N/mm^2)
7 days	36.80	16	5.33	5.33
	39.76	16	5.33	
28 days	38.67	22	7.33	7.5
	39.05	23	7.67	

At the 7-day mark, the flexural strengths recorded for the two specimens are 5.33 N/mm² and 5.33 N/mm², leading to an average flexural strength of 5.33 N/mm². By 28 days, the concrete exhibits a marked improvement in its ability to resist flexural stress. The individual strengths measured are 7.33 N/mm² and 7.67 N/mm², resulting in a higher average flexural strength of 7.5 N/mm². The observed a constant in flexural strength of 5.33 N/mm² at 7 days. At 28 days underscores the effectiveness of steel fibers in improving the bending resistance of concrete, which is a critical property for many structural applications.

Table 4.22 summarizes the compressive strength results for concrete cubes with 10% steel fibers, tested at 7, and 28 days with a water-cement ratio of 0.55.

Table 4.22: at 10% Steel Fibres

Days	Weight of Specimen (kg)	Force (kN)	Flexural Strength (N/mm^2)	Average Flexural Strength (N/mm^2)
7 days	39.39	17	5.67	5.67
	35.64	17	5.67	
28 days	37.70	23	7.67	7.5
	37.14	22	7.33	

The comprehensive test results show the details strength development of the concrete over time. At the 7-day testing interval, the flexural strengths recorded are 5.67 N/mm^2 and 5.67 N/mm^2, resulting in an average flexural strength of 5.67 N/mm^2. By the 28-day mark, the concrete exhibits significantly improved flexural performance. The individual strengths measured are 7.67 N/mm^2 and 7.33 N/mm^2, leading to a higher average flexural strength of 7.5N/mm^2.

Table 4.23 shows the summary of the average flexural strengths for reinforced concrete beams at each percentage steel fibre.

Table 4.23: Summary of average flexural strengths for concrete beams

	Ages (days)	
Percentage Volume Steel Fibre	**7**	**28**
0%	4.67	6.5
2.5%	4.83	7
5%	5.17	7.17
7.5%	5.33	7.5
10%	5.67	7.5

At 7 days and 28 days, the variable factor in this experiment is the percentage of steel fiber reinforcement, ranging from 0% to 10%, with intermediate increments of 2.5%, 5%, and 7.5%. The flexural strength of concrete increases with both age and the percentage of steel fibers added, up to a certain point. For the 7-day old specimens, the flexural strength progresses from 4.67 N/mm^2 for 0% steel fibers to 5.67 N/mm^2 for 10% steel fibers. The 28-day results further emphasize the beneficial effects of steel fibers and the maturation process of concrete. The flexural strength at 28 days is substantially higher across all fiber percentages compared to the 7-day strengths. For the concrete with no fibers (0%), the strength rises to 6.5 N/mm^2. As the steel fiber content increases, the flexural strength also increases, reaching 7 N/mm^2 for 2.5% fibers, 7.17 N/mm^2 for 5% fibers, and peaking at 7.5 N/mm^2 for both 7.5% and 10% steel fibers. This suggests that while increasing steel fiber content generally enhances flexural strength, there might be a saturation point beyond which further additions do not yield proportionally greater improvements, as seen with the 7.5% and 10% samples exhibiting the same average flexural strength.

Figure 4.7 illustrates the relationship between flexural strength (N/mm^2) and varying percentages of steel fiber content. The variation in flexural strength with different curing age is presented in Figure 4.8

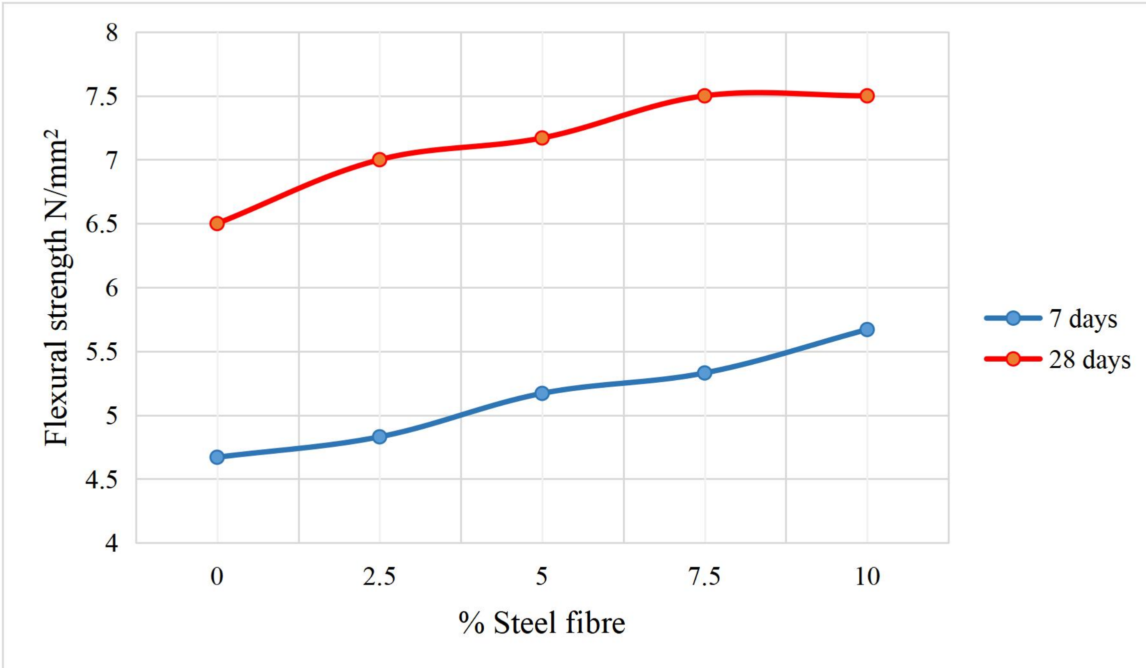

Figure 4.6: Variation of Flexural Strength (N/mm^2) with percentage steel fibre

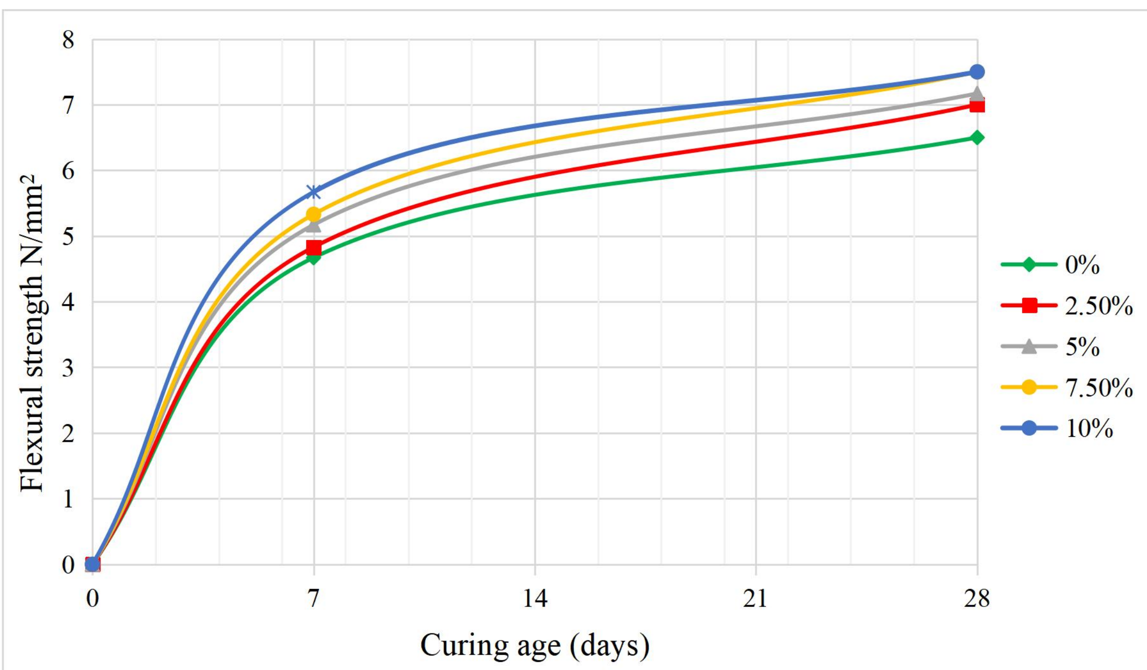

Figure 4. 7: Variation of Flexural Strength (N/mm^2) with curing age

The variation in flexural strength with different steel fiber percentages is presented in Table 4.23.

Discussions

i. From figure 4.6, it was observed that flexural strength of concrete increases with increase in percentage steel fibre. This is an indication that increasing the percentage steel fibre of any concrete will increaseflexural strength. This is also in accordance of the findings of Patil and Rupali. (2014) and Jagadeesh (2016).
ii. From Fig 4.7, the strength values increased as the curing ages increase progressively. This shows the effect of water in the development of strength in normal concrete. It is further observed that the strength development pattern was relatively similar for all the concrete specimens, irrespective of the percentage steel fibre. It was observed that there is a variation of increment in the compressive strength.
iii. It was further observed that the 28-day strengths of all specimens were all reasonably above 6 N/mm^2.

4.6 Crack Pattern and Mode of Failure

Failure was observed in all the beam specimens during the testing process. In most cases, the failure occurred at a small distance away from the midspan (centre) of the beam rather than exactly at the centre. From the observations made during the experiment, the crack patterns and modes of failure were generally similar across all the specimens containing different percentages of steel fibres, as seen in plate 4, appendix 1. No visible cracks were observed prior to the ultimate failure of the beams. The beams failed suddenly without any significant warning signs such as progressive crack development. This behaviour indicates that the mode of failure was brittle in nature, as the specimens did not exhibit noticeable deformation or gradual cracking before collapse.

The sudden and brittle failure of the beams can largely be attributed to the absence of conventional reinforcement steel bars. Reinforcement steel typically plays a critical role in improving the flexural strength and ductility of concrete beams. When reinforcement is present, cracks usually develop gradually in the tension zone, allowing the beam to undergo deformation and provide warning before failure. However, in this study, the exclusion of reinforcement steel limited the beam's ability to redistribute stresses and resist tensile forces, resulting in abrupt failure.

Furthermore, it was observed that the fracture line formed almost straight across the beam, splitting the specimens into two nearly equal halves. This type of fracture pattern suggests that the beams experienced dominant flexural tensile failure, where the tensile stress exceeded the tensile capacity of the concrete matrix. Although steel fibres were incorporated in varying percentages, their presence was not sufficient to significantly alter the overall failure pattern or to prevent the sudden brittle behaviour observed in the specimens. The experimental results indicate that steel fibres contributes to minor improvements in crack resistance and internal bonding, the absence of traditional reinforcement significantly influences the structural performance of concrete beams, leading to sudden brittle failure and minimal crack propagation prior to collapse.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

From this study the following conclusions have been drawn:

The investigation into the strength indices of concrete elements consisting of steel demonstrated that the incorporation of steel fibres produced measurable improvements across all strength indices examined. Compressive strength was found to increase progressively with increasing steel fibre content, with the highest value of 36.81 N/mm² being recorded at 10% steel fibre and the lowest of 15.56 N/mm² obtained from the unreinforced control mix (0% steel fibre). A similar trend was observed in the tensile strength results, where the highest splitting tensile strength of 4.56 N/mm² was achieved at 10% steel fibre content, compared to a minimum of 2.26 N/mm² recorded for the control mix. With respect to flexural strength, an increase was observed with rising steel fibre content; however, it was noted that the rate of increase became progressively less significant beyond the range of 7.5% to 10% steel fibre, suggesting the existence of a saturation threshold beyond which further fibre addition yields diminishing returns in flexural performance. The combined use of steel fibre and steel reinforcement bar was therefore found to enhance the overall structural performance of concrete elements, affirming that such hybrid reinforcement is effective in improving the resistance of concrete to compressive, tensile, and flexural forces.

With respect to understanding the role and effect of steel fibre on the characteristic strength of concrete, the study established that steel fibres act as crack arresters, bridging micro cracks and delaying their propagation, thereby improving tensile and flexural performance. The failure mode of unreinforced concrete beams was observed to be sudden and brittle, with fracture occurring at a short distance from the midspan and without the appearance of visible prior cracking, a behaviour attributed to the absence of conventional reinforcement necessary to provide ductility and redistribute tensile stresses. In contrast, the progressive engagement of steel fibres within the concrete matrix was found to bridge developing micro cracks, thereby delaying crack propagation and enhancing energy absorption capacity while conventional steel reinforcement primarily contributes to load-bearing capacity and ductility, the addition of steel fibres improves post-cracking behaviour and energy absorption capacity. However, an inverse relationship was observed between fibre content and workability, as increasing steel fibre dosage led to reduced slump values due to fibre interlocking and increased internal friction. This highlights the need for proper mix design adjustments when incorporating higher fibre contents to maintain adequate workability without compromising strength. The role of steel fibre in concrete was therefore characterised as that of a dispersed reinforcement mechanism that supplements conventional bar reinforcement in resisting both tensile and shear-induced failure.

That curing age exerted a significant and consistent influence on all strength properties measured. Compressive, tensile, and flexural strengths were each observed to increase with advancing curing age across all fibre content levels, with the maximum values for all tests being attained at 28 days, consistent with the well-established principle that concrete gains strength over time as cement hydration progresses. The highest compressive strength of

36.81 N/mm² and the highest flexural strength of 7.50 N/mm² were both recorded at 28 days for the 10% steel fibre mix, while the corresponding minimum values of 15.56 N/mm² and 4.67 N/mm² were obtained from the control mix at 7 days.

5.2 Recommendations

(i) To improve the ductility and prevent sudden brittle failure of concrete beams, it is recommended to combine steel fibres with traditional reinforcement steel in future tests. This would provide a more realistic assessment of structural performance.

(ii) Further studies should explore different percentages of steel fibre beyond 10% to determine the optimal content for balancing workability, strength, and cost-effectiveness.

(iii) Investigate additional water-cement ratios different from 0.55 to identify the ideal balance between workability and mechanical properties, particularly for high-strength and fibre-reinforced concretes.

(iv) The effect on other structural properties like durability and water absorption can be investigated.

REFERENCES

Abatta-Jacome, L., Rosero-Pazmiño, D., Rosero-Vivas, J., Chávez-Guerrero, B. F., and Barrionuevo, G. O. (2025). Statistical Evaluation of the Mechanical Properties of Welded and Unwelded ASTM A706 Reinforcing Steel Bars of Different Commercial Brands. Metals, 15(12), 1307. https://doi.org/10.3390/met15121307

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

ACI 544.1R (1996). State-of-the-Art Report on Fiber Reinforced Concrete, American Concrete Institute, Farmington Hills, Michigan.

ACI Committee 209. (2023). Guide for modeling and calculating shrinkage and creep in hardened concrete (ACI 209R-23). American Concrete Institute.

Adewuyi, A. P., and Animbom, C. U. (2024). Optimal content and characterisation of steel fibres for crack propagation control and strength enhancement of concrete. Journal of Civil Engineering and Urban Planning, 14(3S), 238–246. https://doi.org/10.14488/JCEU.14.3S.238

Adisa, M.A., Oshadare, S. & Yusuf, Y. Mechanical Properties of Fiber-Reinforced Concrete Using Steel Fibers Derived from Discarded Tires. Int J Concr Struct Mater 20, 22 (2026). https://doi.org/10.1186/s40069-026-00906-4

Afroughsabet, V., and Ozbakkaloglu, T. (2015). Mechanical and durability properties of high-strength concrete containing steel and polypropylene fibers. Construction and Building Materials, 94, 73–82. https://doi.org/10.1016/j.conbuildmat.2015.06.051

Afroughsabet, V., and Ozbakkaloglu, T. (2020). Mechanical and durability properties of high-strength concrete containing steel fibers. Construction and Building Materials, 263, 120139.

Ahmad, J., Zhou, Z., and Deifalla, A. F. (2023). Steel fiber reinforced self-compacting concrete: A comprehensive review. International Journal of Concrete Structures and Materials, 17, 51. https://doi.org/10.1186/s40069-023-00602-7.

Altun, F., Haktanir, T., and Ari, K. (2007). Effects of steel fiber addition on mechanical properties of concrete and RC beams. Construction and Building Materials, 21(3), 654–661. https://doi.org/10.1016/j.conbuildmat.2005.12.006

American Concrete Institute (ACI). (2019). ACI Concrete Terminology. Farmington Hills, MI: ACI.

American Concrete Institute (ACI). (2019). Building code requirements for structural concrete (ACI 318-19) and commentary. ACI.

American Concrete Institute. (2016). ACI 211.1: Standard practice for selecting proportions for normal, heavyweight, and mass concrete. ACI International.

American Concrete Institute. (2018). ACI 544.1R-96 (Reapproved 2018): Report on fiber reinforced concrete.

American Society for Testing and Materials. (2017). ASTM C29/C29M: Standard test method for bulk density ("unit weight") and voids in aggregate. ASTM International.

Amin, M. N., Ahmad, W., Khan, K., and Ahmad, A. (2022). Steel fiber-reinforced concrete: A systematic review of the research progress and knowledge mapping. Materials, 15(17), 6155. https://doi.org/10.3390/ma15176155

ASTM International. (2017). ASTM D2487–17: Standard practice for classification of soils for engineering purposes (Unified Soil Classification System). West Conshohocken, PA: ASTM International.

ASTM International. (2022). ASTM C496/C496M-22: Standard test method for splitting tensile strength of cylindrical concrete specimens. ASTM International. https://doi.org/10.1520/C0496 C0496M-22

ASTM International. (2023). ASTM A615/A615M-23: Standard specification for deformed and plain carbon-steel bars for concrete reinforcement. ASTM International.

Awad, Z. K., Matar, P., and Basha, A. (2023). Flexural and shear behaviour of high-strength concrete beams with hybrid fibre reinforcement and conventional transverse steel bars. Construction and Building Materials, 387, 131612. https://doi.org/10.1016/j.conbuildmat.2023.131612

Balaguru, P. N., & Shah, S. P. (1992). Fiber-reinforced cement composites. McGraw-Hill.

Banthia, N., and Sappakittipakorn, M. (2007). Toughness enhancement in steel fiber reinforced concrete through fiber hybridization. Cement and Concrete Research, 37(9), 1366–1372. https://doi.org/10.1016/j.cemconres.2007.05.005

Bažant, Z. P. (1975). Theory of creep and shrinkage in concrete structures: A précis of recent developments. Mechanics Today, 2, 1–93. https://doi.org/10.1016/B978-0-08-017985-2.50007-3

Bažant, Z. P., & Planas, J. (1998). Fracture and size effect in concrete and other quasibrittle materials. CRC Press.

Boulekbache, B., M. Hamrat, M. Chemrouk and S. Amziane, 2012. Influence of yield stress and compressive strength on direct shear behaviour of steel fibre-reinforced concrete. Constr. Build. Mater., 27(1): 6-14.

Bowles J. E. (1996). Foundation analysis and design (5th ed.). New York, NY: McGraw-Hill.

British Standards Institution. (1971). BS 12: Specification for Portland cement. London: British Standards Institution.

British Standards Institution. (1980). BS 3148: Methods of test for water for making concrete. London: British Standards Institution.

British Standards Institution. (1990). BS 1377-2:1990: Methods of test for soils for civil engineering purposes - Part 2: Classification tests. London: British Standards Institution.

British Standards Institution. (1990a). BS 812-110: Testing aggregates — Methods for determination of aggregate crushing value (ACV). BSI.

British Standards Institution. (1990b). BS 812-112: Testing aggregates — Methods for determination of aggregate impact value (AIV). BSI.

British Standards Institution. (1992). BS 882: Specification for aggregates from natural sources for concrete. BSI.

British Standards Institution. (2007). BS EN 1997-2:2007: Eurocode 7 - Geotechnical design - Part 2: Ground investigation and testing. London: British Standards Institution.

British Standards Institution. (2015). BS 4449: Steel for the reinforcement of concrete - Weldable reinforcing steel - Bar, coil and decoiled product—Specification. BSI.

Broomfield, J. P. (2007). Corrosion of steel in concrete: Understanding, investigation and repair (2nd ed.). Taylor and Francis.

BS 8110 Part 1. "Structural Use of Concrete", British Standards Institution, London. BSI London, 1997. 321-327.

Chen, X., Zhang, M., and Wang, Y. (2022). Shear behavior of steel fiber reinforced concrete beams with high-strength reinforcement. Engineering Structures, 267, 114679. https://doi.org/10.1016/j.engstruct.2022.114679

Das B. M. (2010). Principles of geotechnical engineering (7th ed.). Stamford, CT: Cengage Learning.

Dixon, J. and Mayfield, B. 1971. Concrete reinforced with fibrous wire. Journal of the Concrete Society, Concrete, 5, 73-76.

El Bakzawy, A., Makhlouf, M. H., Mustafa, T. S., and Adam, M. (2024). Experimental investigation on the flexural behavior of SFRC beams reinforced with hybrid reinforcement schemes. Engineering Structures, 309, 118054. doi.org

Engineering Toolbox. (2023). Concrete properties. engineeringtoolbox.comhttps://www.engineeringtoolbox.com/concrete-properties-d_1223.html

Esfandeh, M., Sabet, A.R., Rezadoust, A.M. and Alavi, M.B. (2009), Bond performance of FRP rebars with various surface deformations in reinforced concrete. Polym Compos, 30: 576-582. https://doi.org/10.1002/pc.20589

Federal Highway Administration (FHWA). (2012). Estimation of key PCC, base, subbase, and pavement engineering properties from routine tests and physical characteristics (FHWA-HRT-12-030). U.S. Department of Transportation. https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/ltpp/12030/004.cfm

Fib International Federation for Structural Concrete. (2013). fib Model Code 2010. Ernst and Sohn.

Figueiredo, A. D., and Ceccato, M. R. (2015). Workability analysis of steel fiber reinforced concrete using slump and Ve-Be test. Materials Research, 18(6), 1284–1290. https://doi.org/10.1590/1516-1439.022915

Gagg, C.R. (2014). Cement and Concrete as an engineering material: an historic appraisal and case study analysis. Engineering Failure Analysis. 40. 10.1016/j.engfailanal.2014.02.004.

GarcIa-Taengua E, Arango S, MartI-Vargas JR, and Serna P. (2014) Flexural creep of steel fiber reinforced concrete in the cracked state. Construction and Building Materials 2014; 65:321-9. doi:10.1016/j.conbuildmat.2014.04.139.

García-Taengua, E., Marti-Vargas, J. R., and Serna-Ros, P. (2021). Residual flexural strength of SFRC: A multivariate perspective. Construction and Building Materials, 326, 126751. https://doi.org/10.1016/j.conbuildmat.2022.126751

Gong, C., Kang, L., Zhou, W., Liu, L., and Lei, M. (2023). Tensile performance test research of hybrid steel fibre-reinforced self-compacting concrete. Materials, 16(3), 1114. https://doi.org/10.3390/ma16031114

Gong, J., Chen, L., Li, H., and Zhang, Y. (2023). Digital image correlation analysis of crack behavior in hybrid steel fibre reinforced self-compacting concrete beams. Cement and Concrete Composites, 139, 104998. https://doi.org/10.1016/j.cemconcomp.2023.104998

Guo, Z., Liu, X., Zhang, H., and Wang, L. (2025). Bending characteristics of steel fiber reinforced concrete beams with hybrid steel and GFRP bar reinforcement. Composite Structures, 330, 117847. https://doi.org/10.1016/j.compstruct.2024.117847

Hassan, H.Z., Saeed, N.M. Fiber reinforced concrete: a state of the art. Discov Mater 4, 101 (2024). https://doi.org/10.1007/s43939-024-00171-w

Holschemacher K, Weisse D. Bond of reinforcement in fibre reinforced concrete, Varenna, Italy: 2004.

Hong. S, Choi, J.S., Yuan, T. F, and Yoon, Y.S (2023). A review on concrete creep characteristics and its evaluation on high-strength lightweight concrete*, Journal of Materials Research and Technology,* 22, 230-251

Huang, C., Hadjipantelis, N., Quan, S., Chen, T., Gardner, L. (2024). Mechanical properties of wire arc additively manufactured steels at polar temperatures, Structures. 70 ,107627. https://doi.org/10.1016/j.istruc.2024.107627

Jackson, N., and Dhir, R. K. (Eds.). (2015). Civil engineering materials (5th ed.). Red Globe Press.

Johnston, C. D. 1974. Steel fiber reinforced mortar and concrete: a review of mechanical properties. http ://www.britannica.com/EBchecked/topic/496607reinforced-concrete. (Accessed on: 9/04/2015).

Johnston, C.D, Cohn, D. (1982). Fibre Reinforced Concrete. Progress in Concrete Technology CANMET, *Energy, Mines and Resources*, Canada, 2 15-236.

Kakooei,S., Akil, H.M., Jamshidi, M. and Rouhi, J., 2012. The effects of polypropylene fibers on the properties of reinforced concrete structures. Construction and Building Materials, 27, 73-77.

Karzad, A. S., Leblouba, M., Al-Sadoon, Z. A., Maalej, M., and Altoubat, S. (2023). Modeling the flexural strength of steel fibre reinforced concrete. AIMS Materials Science, 10(1), 86–111. https://doi.org/10.3934/matersci.2023006

Khaloo, A. R., and Afshari, M. (2005). Flexural behaviour of small steel fibre reinforced concrete slabs. Cement and Concrete Composites, 27(1), 141–149. https://doi.org/10.1016/j.cemconcomp.2004.03.004

Khaloo, A. R., and Kim, N. (1997). Influence of concrete and fiber characteristics on behavior of steel fiber reinforced concrete under direct shear. ACI Materials Journal, 94(6), 592–601. https://doi.org/10.14359/344

Koo, D.-H., Kim, J.-S., Kim, S.-H., and Suh, S.-W. (2023). Evaluation of Flexural Toughness of Concrete Reinforced with High-Performance Steel Fiber. Materials, 16(20), 6623. https://doi.org/10.3390/ma16206623

Kosmatka, S. H., and Wilson, M. L. (2016). Design and control of concrete mixtures (16th ed.). Portland Cement Association.

Li, B., Wu, H., Zhang, L., and Chen, J. (2024). Structural performance of SFRC–normal concrete composite beams with steel fibre applied in the tensile layer. Construction and Building Materials, 415, 135093. https://doi.org/10.1016/j.conbuildmat.2024.135093

Liu, J., Wei, L., Cui, Q., Shu, H., Peng, W., Gong, H., Xue, Y., and Han, M. (2025). Chloride Corrosion Resistance of Steel Fiber-Reinforced Concrete and Its Application in Subsea Tunnel Linings. Coatings, 15(2), 235. https://doi.org/10.3390/coatings15020235

Liu, K., Zhang, C., Liu, Q., Peng, J., and He, Z. (2024). Mechanical properties of steel fiber-reinforced rubber concrete after elevated temperature. Scientific Reports, 14, 4859. https://doi.org/10.1038/s41598-024-80458-3

Mangat, P. and Gurusamy, K. (1987). Permissible crack widths in steel fibre reinforced marine concrete. Materials and Structures, 20, 338–347.

Meddah, M.S. and Bencheikh, M., 2009. Properties of concrete reinforced with different kinds of industrial waste fibre materials. Construction and Building Materials, 23, 3196-3205.

Mehrabi, P., Dackermann, U., Siddique, R., and Rashidi, M. (2024). A Review on the Effect of Synthetic Fibres, Including Macro Fibres, on the Thermal Behaviour of Fibre-Reinforced Concrete. Buildings, 14(12), 4006. https://doi.org/10.3390/buildings14124006

Mehta, P. K., and Monteiro, P. J. M. (2014). Concrete: Microstructure, properties, and materials (4th ed.). McGraw-Hill Education.

Mochane, M. J., Mokhena, T. C., Mokhothu, T. H., Mtibe, A., Sadiku, E. R., Ray, S. S., Ibrahim, I. D., and Daramola, O. O., (2019). Recent progress on natural fiber hybrid composites for advanced applications: A review. eXPRESS Polymer Letters 159–198

Mohamed, S., Elemam, H., Seleem, M. H., and Sallam, H. E. D. (2024). Effect of fiber addition on strength and toughness of rubberized concretes. Scientific Reports, 14(1), 4346. https://doi.org/10.1038/s41598-024-54763-w

Mujalli, M. A., Dirar, S., Mushtaha, E., Hussien, A., and Maksoud, A. (2022). Evaluation of the Tensile Characteristics and Bond Behaviour of Steel Fibre-Reinforced Concrete: An Overview. Fibers, 10(12), 104. https://doi.org/10.3390/fib10120104

Naaman, A. E. 1985. Fiber reinforcement for concrete. Concrete International, 7, 21-25.

Narayanan, R., and Darwish, I. (1987). Bond Anchorage of Pretentioned FRP Tendon at Force Release. ASCE Journal of Structural Engineering, 118: No. 10, 2837-2854.

Neville, A. M. (2011). Properties of concrete (5th ed.), Pearson Education Limited.

Neville, A. M., and Brooks, J. J. (2021). Concrete Technology (3rd ed.). Pearson Education.

Nilson, A. H., Darwin, D., and Doland, J. L. (2010). Design of concrete structures (14th ed.). McGraw-Hill.

Niu, Y., Wei, J., and Jia, J. (2023). Experimental investigation on the flexural behavior of concrete reinforced by various types of steel fibers. Frontiers in Materials, 10, 1301647. https://doi.org/10.3389/fmats.2023.1301647

Noguchi, T., Tomosawa, F., Nemati, K. M., Chiaia, B. M., and Fantilli, A. P. (2009). A practical equation for elastic modulus of concrete. ACI Structural Journal, 106(5), 690–696. https://doi.org/10.14359/56785

Okonta, D. E., Vukovic, V., Segovia, E., and Akinola, A. (2023). Building Information Modelling (BIM)-based Quality Management System (QMS) for mitigating building failures and collapse: A case study of Nigeria. In M. P. Brito, T. Aven, P. Baraldi, M.

Čepin, & E. Zio (Eds.), Proceedings of the 33rd European Safety and Reliability Conference (ESREL 2023*)*. Research Publishing.

Oyelade O. A., Olusanya N. A., Inyangson I. E., Adeoye P. G., and Obaji O. N. (2024). The influence of granite size and workability on the compressive strength of continuous flight auger pile concrete. FUOYE *Journal of Engineering and Technology*, 9(1), 135–140.

Padmarajaiah, S. and Ramaswamy, A. 2002. A finite element assessment of flexural strength of prestressed concrete beams with fiber reinforcement. Cement and Concrete Composites, 24, 229-241.

Pham, T.M (2025). Fibre-reinforced concrete: State-of-the-art-review on bridging mechanism, mechanical properties, durability, and eco-economic analysis. Case Studies in Construction Materials. 22, https://doi.org/10.1016/j.cscm.2025.e04574

Raheem, A. B., and Klak, F. S. (2024). Shear strength of conventional and lightweight concrete I-beams with fibrous webs. Engineering, Technology & Applied Science Research, 14(5), 16486–16491. https://doi.org/10.48084/etasr.8155

Ramazani, P., Moradi Shaghaghi, T., and Farzam, M. Flexural Strength of Light-Weight Steel Fiber Reinforced Concrete Containing Biodegradable LDHs Microparticles: Experimental Study and Multiscale Finite Element Model. Int J Concr Struct Mater 18, 37 (2024). https://doi.org/10.1186/s40069-024-00667-y

Rappl, S.; Hameed, S., M.Z.; Krempaszky, C.; Osterminski, K. (2023). Mechanical and Surface Geometric Properties of Reinforcing Bars and Their Significance for the Development of Near-Surface Notch Stresses. Mathematics, 11, 1910. https://doi.org/10.3390/math11081910

Ren, X., Xie, Y., Ding, F., Sun, D., and Liu, H. (2024). Steel Fiber Reinforced Concrete: A Systematic Review of Usage in Shield Tunnel Segment. Sustainability, 16(24), 10832. https://doi.org/10.3390/su162410832

Reynolds, C.E. and Steedman, J.C. Reinforced Concrete Designer's handbook, 10th edition, E and FN Spon, Taylor and Francis Group, 1988.

Romualdi, J. P., and Batson, G. B. (1963). Mechanics of crack arrest in concrete. Journal of the Engineering Mechanics Division, ASCE, 89(3), 147–168. https://doi.org/10.1061/JMCEA3.0000430

Shayan, J. A., Peiris, S. R., and Coorey, R. V. (2010). Study of elastic properties of reinforcing steel bars. Proceedings of the Technical Sessions, 26, 67-74. 1.3.1, 1.3.2

Shetty M. S. (2005). Concrete technology: Theory and practice. New Delhi, India: S. Chand and Company Ltd.

Shiferaw, H. N., and Kanakubo, T. (2025). Structural Performance of Fiber-Reinforced Cementitious Composite Members Reinforced with Fiber-Reinforced Polymer Bars: A Systematic Review. Applied Sciences, 15(14), 7681. https://doi.org/10.3390/app15147681

Simeon Stoyanov Cite this: Chem. Soc. Rev., 2012, 41, 4708–4735 Electrospinning versus fibre production methods: from specifics to technological convergence

Specification for Steel for Bridges and Building, American Society for Testing and Materials, ASTM A7, 1967 2012, pp. 1-13.

Standards Organisation of Nigeria. (2003). NIS 441-1:2003: Cement — Part 1: Composition, specifications and conformity criteria for common cements. Abuja: Standards Organisation of Nigeria.

Standards Organisation of Nigeria. (2003). NIS 441-2:2003: Cement — Part 2: Conformity evaluation. Abuja: Standards Organisation of Nigeria.

Su, M.-N, Young, B., Gardner, L., (2014). Deformation-based design of aluminum alloy beams, Engineering Structures, 80 (339-349)

Tadepalli, P. R., Mo, Y. L., and Hsu, T. T. C. (2013). Mechanical properties of steel fibre concrete. Magazine of Concrete Research, 65(8), 462–474.

Thomas, J., and Ramaswamy, A. (2007). Mechanical properties of steel fiber-reinforced concrete. Journal of Materials in Civil Engineering, 19(5), 385–392. https://doi.org/10.1061/(ASCE)0899-1561(2007)19:5(385)

Turatsinze, A., Granju, L., Sabathier, V. and Farhat, H. 2005. Durability of bonded cement-based overlays: effect of metal fibre reinforcement. Materials and structures, 38,

Vijayan, D. S., Sivasuriyan, A., Parthiban, D., Jakimiuk, A., Bayat, H., Podlasek, A., Vaverková, M. D., and Koda, E. (2022). A Comprehensive Analysis of the Use of SFRC in Structures and Its Current State of Development in the Construction Industry. Materials, 15(19), 7012. https://doi.org/10.3390/ma15197012

Wan, Y., Liu, Z., Zhang, B., and Li, K. (2024). Effects of varying steel fibre content and rebar reduction on crack control in tunnel lining segments. Tunnelling and Underground Space Technology, 145, 105578. https://doi.org/10.1016/j.tust.2024.105578

Wang, B., Lv, H., Gao, Y., Tang, M., Ding, N., Zhao, X., and Hu, X. (2024). Experimental study on axial compressive performance of recycled steel fiber reinforced concrete short columns. Buildings, 14(8), 2498. https://doi.org/10.3390/buildings14082498

Wang, H., Lin, J., and Guo, S. (2025). Study on the compressive strength prediction of steel fiber reinforced concrete based on interpretable deep learning. Applied Sciences, 15(12), 6848. https://doi.org/10.3390/app15126848

Woodward, R. and Duffy, N., 2011. Cement and concrete flow analysis in a rapidly expanding economy: Ireland as a case study. Resources, Conservation and Recycling, 55, 448- 455.

Xie, J., Li, J., Wu, Z., Chen, J., and Liu, F. (2023). A review on fracture properties of steel fiber reinforced concrete. Journal of Building Engineering, 67, 105977. https://doi.org/10.1016/j.jobe.2023.105977

Xing, L., Sun, S., Mei, K., Guo, Y., and Yang, Z. (2024), Research progress on short-term mechanical properties of FRP bars and FRP-reinforced concrete beams, Journal of Traffic and Transportation Engineering (*English Edition*), 11(2), 245-270

Yang, J., Zhang, Y., and Huang, J. (2024). The strengthening theory of steel fiber reinforced concrete and its application in tunnel engineering: A review. *Journal of Composite Materials and Engineering*, 6(1), 15239242 https://doi.org/10.1177/15589250241239242

Yazıcı, Ş., İnan, G., and Tabak, V. (2007). Effect of aspect ratio and volume fraction of steel fiber on the mechanical properties of SFRC. Construction and Building Materials, 21(6), 1250–1253. https://doi.org/10.1016/j.conbuildmat.2006.05.025

Yoo, D. Y., Dashtaki, S.S, Oh, T., Chun, B., Choi, J.S., Banthia, N, and Yoon, Y. S. (2024). Effects of amount and geometrical properties of steel fiber on shear behavior of high-strength concrete beams without shear reinforcement. Cement and Concrete Composites, 151, 105606. https://doi.org/10.1016/j.cemconcomp.2024.105606

Yoo, D.Y., and Banthia, N. (2022). Mechanical properties of ultra-high-performance fiber-reinforced concrete: A review. Cement and Concrete Composites, 73, 267–280.

Yoo, D.Y., Yoon, Y.S., and Banthia, N. (2015). Flexural response of steel-fiber-reinforced concrete beams: Effects of strength, fiber content, and strain-rate. Cement and Concrete Composites, 64, 84–92. https://doi.org/10.1016/j.cemconcomp.2015.10.001

Yusuf, M. S., Isak, A. B., Mohamud, G. A., Warsame, A. H., Osman, Y. I., Ibrahim, A. H., and Elmi, L. A. A. (2023). Effect of steel fiber on concrete's compressive strength. Open Journal of Civil Engineering, 13(1), 192–197. https://doi.org/10.4236/ojce.2023.131014

Zhang, H., Tang, Z., Li, J., Hu, Z., and Feng, Q. (2025). Experimental Investigation on Toughness of SFRC and Bond Behavior with Reinforcing Bars. Buildings, 15(2), 274. https://doi.org/10.3390/buildings15020274

Zhao, M., Li, J., Li, C., and Shen, J. (2024). Effectiveness evaluation of different steel fibers on the shear strength of reinforced SFRC slender beams without web rebars. Scientific Reports, 14, 21249. https://doi.org/10.1038/s41598-024-71574-1

Zheng, Y., Lv, X., Shaowei Hu, Jingbo Zhuo, Cong Wan, and Jiaqi Liu, 2024. Mechanical properties and durability of steel fiber reinforced concrete: A review, *Journal of Building Engineering,* 82, Article 108025.

APPENDIX I

(PICTURES FROM LABORATORY EXPERIMENTS)

Plate 1: A weighing balance measuring the mass of a sample

Plate 2: A set of BS sieves for sieve analysis

Plate 3: Lubrication of Cube Moulds in preparation for casting

Plate 4: Crushed Cube Specimens

Plate 5: Crack pattern and Mode of failure of beam specimen

APPENDIX II

Average compressive strengths for concrete cubes at various percentage steel fibre

Ages (days)				
Percentage Volume Steel fibre	7	14	21	28
0%	15.56	17.85	20.89	24.44
2.5%	17.48	21.48	24.08	26.74
5%	19.18	22.37	25.18	30.15
7.5%	22.07	25.93	29.26	32.3
10%	25.85	27.55	32.52	36.81

Average tensile strengths of concrete cubes at various percentage steel fibre

Ages (days)				
Percentage Volume Steel Fibre	7	14	21	28
0%	2.26	2.87	3.25	3.54
2.5%	2.76	2.9	3.51	4.03
5%	2.83	3.29	3.65	4.25
7.5%	3.11	3.43	3.68	4.28
10%	3.43	3.5	4.14	4.56