

**STRENGTH PROPERTIES OF CONCRETE INCORPORATING
PINE NEEDLE AND SISAL FIBRE COMPOSITES**

BY

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23/U/GMES/1246/PE

**A DISSERTATION SUBMITTED TO THE DIRECTORATE OF
RESEARCH AND GRADUATE TRAINING IN PARTIAL
FULFILLMENT OF THE REQUIREMENTS FOR THE
AWARD OF MASTER OF SCIENCE IN
STRUCTURAL ENGINEERING DEGREE
OF KYAMBOGO UNIVERSITY**

NOVEMBER, 2025

DECLARATION

This dissertation entitled “*strength properties of concrete incorporating pine needle and sisal fibre composites*” is my own work and that, to the best of my knowledge and belief, it neither contains material previously published or written by another person nor material which has been accepted for the award of a degree of any University or other institute of higher learning.

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APPROVAL

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ACKNOWLEDGEMENTS

I extend my deepest gratitude to my academic supervisors, Dr. Vicent Ssenyondo, Dr. Eng. Morris Oleng and Dr. Eng. Sam Bulolo for their tireless commitment, unwavering support, and expert guidance throughout my research journey. Their selfless dedication, patience, and encouragement went beyond mere academic supervision, nurturing me to grow and thrive. I also thank my parents, Demeterina Ariso, Silver Onyango, and my beloved grandmother Martina Ikwenyu, for their unconditional love, prayer and support, Kyambogo University for providing a rich academic environment. I finally extend my sincere gratitude to the Central Materials Laboratory, Ministry of Works and Transport, Kampala-Uganda, specifically the chief materials Engineer, the secretary, the technical laboratory staff, for their significant support, contribution especially for granting me access to the laboratory facilities that enabled the successful execution of my experimental research. This dissertation is a testament to the great power of collaboration, perseverance, commitment, faith in the intelligence of the universe, God, and dedication, and I hope it contributes meaningfully to the field of Construction Materials and Structural Engineering.

DEDICATION

I dearly dedicate this dissertation to my family, who have greatly given me a hand to lean on throughout my academic journey, my parents Demeterina Ariso and Silver Onyango, my mentors Dr. Eng. Morris Oleng, Dr. Vicent Ssenyondo, Dr. Charles Onyutha, Dr. Michael Kyakula, Fr. Romanus Etwap, and Fr. Micheal Omaria. My dear brothers Joseph Odongo, Silver Onyango, Moses Osege, Sister Hannah Akwaso, Jeniffer Adego, and Immaculate Akello, my dear friends Susan Akello Ariis, Busingye Diana, Hellensie, Barnabus Atukwase, CE Linda, Pative Ameo, A Sammie, S Kongola, Avaga Savior, Joram, W Tim, J. Kennedy Omanga, Dr. Fidrella Rowenah, Arinaitwe Wiston, Patrie and many others, who have supported and provided me with a shoulder to lean on during the research process. I finally dedicate this thesis to the pursuit of knowledge and innovation for sustainable material development in the field of Structural Engineering across the globe.

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ABBREVIATIONS AND ACRONYMS

CN	:	CentiNewtons
CO ₂	:	Carbon dioxide
DC	:	Direct Cost
FRC	:	Fibre Reinforced Concrete
IC	:	Indirect Cost
Kg	:	Kilogram
LCA	:	Life Cycle Analysis
MPa	:	Megapascal
MoLHUD	:	Ministry of Lands, Housing and Urban Development
NFA	:	National Forestry Authority
NFRC	:	Natural Fibre Reinforced Concrete
OPC	:	Ordinary Portland Cement
PNF	:	Pine Needle Fibre
ROM	:	Rule Of Mixtures Theory
RC	:	Reinforced Concrete
SDG	:	Sustainable Development Goals
SF	:	Sisal Fibre
TC	:	Uganda Total Cost
UN	:	United Nations
UNECE	:	United Nations Economic Commission for Europe
EUNEP	:	United Nations Environmental Program

ABSTRACT

The construction industry's reliance on traditional materials has significant unprecedented material, economic, and environmental challenges. The urgent need for sustainable and environmentally friendly building materials has become increasingly important towards abating environmental degradation. Concrete, a widely used construction material, can benefit from the incorporation of natural fibres, which can improve on its mechanical properties whilst reducing its environmental-related footprint. The main objective of this study was to develop an optimum cost-effective, environmentally sustainable pine needle and sisal fibre reinforced concrete composite with enhanced strength properties. More specifically, this study evaluated the physical and mechanical properties associated with the performance of pine needle and sisal fibres as concrete ingredients, assessed the effect of pine needle and sisal fibre content on concrete strength and determine the optimal fibre content for achieving desired mechanical properties, and examined the durability and economic viability including the environmental benefits of pine needle and sisal fibre reinforced concrete composites. The methodological scope of this study involved an experimental approach, where the strength properties of concrete were evaluated under various fibre dosages (for single fibre type: 0.1%, 0.2%, 0.5%, 1%, 1.5% and 2% and for hybrid (0.1%+0.1%, 0.2%+0.2%, 1%+0.5%, 0.5%+1% sisal and pine needle fibre respectively. Sigma plot and ANOVA were used in data analysis, presentation and determination of the statistical significance of the perceived variance. The optimal fibre content for compressive strength was found to be 0.1%, while 0.2% by weight was optimal for split tensile strength. The results showed that addition of pine needle and sisal fibres led to reduction in compressive strength by 19.1% and a reduction in flexural strength by 2.5% compared to plain concrete. However, a notable increment of 21.7% was recorded for the split tensile strength. Despite reductions in some strength properties, the design concrete strength class of 20 N/mm² was still achieved. A cost-benefit analysis revealed that using fibres resulted in a cost savings of Ugandan shillings 55,000 in 0.36m³. The carbon dioxide emissions analysis showed that whereas using steel reinforcement would result in 34.4 kilograms of CO₂ emission, the use of fibres would result in emissions of only 5.28 kilograms of CO₂ emission, this study demonstrated an innovative approach into sustainable material development.

CHAPTER ONE: INTRODUCTION

1.1 Background of the study

The construction industry is one of the largest consumers of natural resources and as such, the global sector significantly contributes to environmental degradation ([Vasilca et al., 2021](#)). In recent decades, the construction industry faces unprecedented material sustainability challenges, with high waste generated, environmental degradation and high construction costs persistently increasing globally ([Ainun Musir et al., 2022](#)). The industry's influence extends far beyond environmental concerns, with a profound impact on the global economy. With approximately US\$10 trillion, accounting for around 13% of the world's economic output with the projections estimated to grow up to US\$17.5 trillion by 2030 at a rate of 4% annually ([Paknahad et al., 2025](#)). As the industry continues to expand, developing strategies that simultaneously optimize cost and embodied carbon through Mult objective approaches has become highly crucial for sustainable development ([Malik et al., 2024](#)).

Infrastructure development serves as a cornerstone for economic growth and societal advancement, playing a pivotal role in development of many countries across the world ([Gorgulu et al., 2023](#)). Africa's economic ascension hinges on infrastructure development, yet the continent faces a significant innovation gap. The sub-Saharan Africa's debt-to-GDP ratio has more than doubled in just over a decade, skyrocketing from 23.2% in 2008 to 57.1% in 2022, with projections expectations indicating a prolonged plateau at this level until 2029 ([Africa Finance Corporation, 2024](#)). This alarming trend heightens the risk of debt distress, casting a shadow over the region's ability to secure vital funding for infrastructure development, yet it's a crucial issue for its sustainability.

Uganda's urban landscape is undergoing rapid transformation, with built-up areas expanding by 70% between 2010 and 2019, reaching 1589.7 km². Paradoxically despite this growth, key challenges hindering sustainable development include unplanned settlements, climate change vulnerabilities, sustainability concerns, and inadequate infrastructure ([MoLHUD, 2022](#)). The increasing demand for infrastructure development has led to surge in concrete consumption, resulting in high CO₂ gas emission and environmental degradation ([Dixon, 2010](#)). The construction materials like concrete, steel and timber not only exhaust natural resources but also contribute to carbon emissions and waste generation ([UNEP, 2024](#)). Bridging these gaps require strategic innovative approaches and financing solutions to unlock the potential of its transportation networks, including ports, railways, roads and airports ([Gorgulu et al., 2023](#)). In response to these challenges, there is an urgent need to develop sustainable construction materials that reduce environmental concerns in line with SDG 11: Sustainable cities and communities ([UNU, 2020](#)).

One area of research that avails hope is the utilization of agricultural and forestry residues as a raw material for building composites and sustainable development ([Havrysh et al., 2021](#)), aligning with SDG 13 on climate action. Natural fibres such as pine needle and sisal fibres offer potential benefits, including renewability, low maintenance costs, environmental benefits, sustainability, and energy efficiency ([Shrestha et al., 2024](#)). In addition the global natural fibre composite market is poised for rapid growth, with projections indicating a compound annual growth rate of 9.95% and evaluation exceeding US\$41 billion by 2026 ([Malik et al., 2024](#)).

Although the incorporation of natural fibres may have limitations, (e.g., low tensile strength compared to steel and susceptibility to degradation and moisture damage), the combination of more fibres can lead to improved strength, durability and toughness ([Maiti et al., 2022](#)). Engineers are increasingly exploring the potential of natural fibres as a valuable additive in concrete, driven by the pursuit of innovation due to the sustainable challenges and the attractive properties found in the natural fibres ([Sethunarayanan et al., 2007](#)). Natural fibres such as pine needle, bamboo fibres, jute fibre and sisal fibre have emerged as viable alternatives for modern innovations ([Karimah et al., 2021](#)). More over previous studies indicate that the mechanical interlocking between the concrete and the fibre matrix plays a critical role in improving concrete strength properties ([Hamada et al., 2023](#)).

While many of the researches have been conducted on the use of various natural fibres (e.g., [Yusra et al., 2024](#) and [Kurpińska et al., 2022](#)), a variety of these researches have investigated the mechanical attributes of fibre reinforced concrete using individual fibres such as bamboo, coconut, Jute, Banana fibres as a material for enhancing in structural concrete. There is need for more exploration of natural fibres for more innovations and development of sustainable building materials ([Siouta et al., 2024](#)).

The specific effect of incorporating pine needle and sisal fibres as hybrid materials e.g. on concrete strength properties, including optimal fibre proportions, durability and their interaction with the concrete matrix remains under explored. Furthermore, the limited availability of advanced technological sustainable construction materials practices in developing countries (e.g. the East African region) undermines SDG 11: Sustainable Cities and Communities ([UNECE, 2025](#)). Addressing these gaps and changing

the perspective onto natural fibre utilization can provide valuable insights and contribute to the creation of more sustainable, durable, low cost and high-performance building substances including concrete composites ([Krifa and Gnanasekar, 2025](#)).

1.2 Problem statement

The building industry is one of the main drivers of environmental harm, contributing significantly to the degradation of natural ecosystem, accounting for approximately (45-50) % of global energy consumption, 50% water consumption, 25% direct rain forest destruction ([Dixon, 2010](#)). On average, according to [World Steel Association \(2021\)](#), about 1.85 tonnes of carbon dioxide gas was emitted into the atmosphere in 2019. In 2020, 1860 million tonnes of steel was produced causing direct emissions of 2.6 billion tonnes of carbon dioxide gas representing 7 – 9% of the global anthropogenic CO₂ gas emissions

Although concrete remains one of the world's most utilized construction material ([Golewski, 2023](#)), its limitations, particularly brittle nature, characterised by its inability to withstand significant deformation, poses significant challenge ([Abdel Hafez et al., 2024](#)). Furthermore, conventional concrete's inherent susceptibility to cracking underscores the need for innovative solution. Concrete's limited tensile strength compromises its durability, often leading to crack propagation and sudden failures ([Raghoo et al., 2021](#)). Modern high-performance concrete as a material must balance eco-friendly and low-carbon requirements with enhanced toughness, ensuring structural resilience and safety in the face of potential fracture ([Malik et al., 2024](#))

The increased need and demand for infrastructural development has led to rise in concrete consumption, resulting in high CO₂ gas emission and environmental degradation, pollution and fossils ([Malik et al., 2024](#))

The upsurge production of steel with the aim to improving concrete strength properties has led to the exhaustion of natural available material substances (e.g., iron and coal) and generation and disposal of hazardous waste; this waste includes scrap from steel use. According to [Reuter \(2022\)](#), 66.9 million tonnes of scrap were globally recycled, these represents the waste generated in the year 2020, this is a huge threat to the surrounding and sustainable development. This poses a significant threat to achieving sustainable development goal (SDG 13): Climate action and SDG 9: industry, innovation and infrastructure ([Link et al., 2017](#))

To mitigate these limitations and concurrently address pressing environmental concerns, the adoption of natural substances into concrete offers a key solution, potentially enhancing concretes mechanical attributes and providing innovative sustainable alternatives ([Veerappan et al., 2024](#)). Natural fibre-improved concrete has come out as a hope giving alternative, offering important key benefits ([Shah et al., 2022](#)), including enhanced strength and resilience ([Hamada et al., 2023](#)). In today's study, the knowledge gap lies in deriving alternatives to the predominant use of traditional materials, which only exacerbates environmental concerns and hinders the progress towards SDG 12: Responsible production and Consumption which most countries have failed to achieve across the world. The lack of adequate knowledge on optimized fibre ratios for enhanced concrete strength properties, durability of natural fibre reinforced concrete (NFRC) composites poses need for further research ([Hait et al., 2024](#)). This study aimed to contribute to the development of sustainable building material by exploring the

strength properties of concrete incorporating pine needle and sisal fibre composites, aligning with SDG 9: industry, infrastructure, creative innovation and SDG 13: Climate action ([United Nations Uganda, 2020](#))

1.3 Objectives of the study

1.3.1 Main objective

To develop an optimum cost-effective, environmentally sustainable pine needle and sisal fibre reinforced concrete composite with enhanced strength properties.

1.3.2 Specific objectives

1. To evaluate the physical and mechanical properties associated with the performance of pine needle and sisal fibres as concrete ingredients.
2. To assess the effects of pine needle and sisal fibre content on concrete strength and determine optimal fibre content.
3. To examine the durability properties of pine needle and sisal fibre reinforced concrete composite.
4. To evaluate the economic viability and environmental benefits of pine needle and sisal fibre-reinforced concrete.

1.4 Research questions

1. What physical and mechanical properties of pine needle and sisal fibres contribute to their performance as concrete ingredients?
2. To what extent does fibre content influence the strength properties of concrete?
3. How do the hybrid fibres interact to modify the durability properties of concrete?

4. To what extent is pine needle and sisal fibre reinforced concrete economically viable and environmentally beneficial?

1.5 Justification of the research

The global building and construction industry is facing major challenges in achieving sustainable and environmentally friendly building practices ([Cousins, 2022](#)). The construction industry faces pressing sustainability challenges particularly in countries of Global South, where environmental degradation and high construction costs remain persistent ([Ogunmakinde et al., 2016](#)). Africa's infrastructures gap is stark, with annual needs ranging from US\$130 billion to US\$170 billion, yet current commitments hover around US\$80 billion per year, leaving a significant shortfall. While Africa struggles taking the lead in infrastructure financing, the investors support by about US\$40 billion annual ([Africa Europe Foundation 2025](#)).

The prevalence of sustainable challenges for example high CO₂ emission and environmental degradation triggers the need for research with an urgent need to provide solutions to these construction challenges ([Simplice, 2021](#)). Therefore, there is a pressing need to develop economical, eco-friendly and sustainable construction materials. Natural fibres such as bamboo, pine needles, jute and sisal fibres abundance, in tropical regions, offer potential as sustainable materials ([Sengupta, 2024](#)). These fibres have been used traditionally for some applications; for instance board formations, nanocellulose, heavy metal absorption, soil slope stabilization, bags, and crafts ([Strategies, 2024](#)).

However there has been a gap for their broader research exploration as sustainable building materials especially in enhancing concrete strength properties.

Combining more fibres and leveraging their mechanical properties can improve the overall composite material performance. Improved mechanical properties of hybrid fibres (Jeff Jomboh et al., 2024) e.g., sisal fibre enhance split tensile strength while pine needle fibres improve flexural strength and allow larger deformations due to their large diameter compared to sisal. It also improves on a load bearing capacity and stiffness. There is durability enhancement of fibre composites due to their combined synergistic effect and resistance (Jeff Jomboh et al., 2024) e.g., sisal fibres are resistant to alkaline degradation compared to pine needle fibres, the combination of fibres can reduce the risk of fibre degradation due to their synergistic effect (Kim, 2014). Environmental benefit, both fibres can be reused, decomposable, and sustainable, hence reduced carbon percentage compared to artificial fibres.

In summary, this study has demonstrated the significant effects of pine needle and sisal fibres on the concrete strength properties with yields on the optimal fibre contents, it has also provided valuable insights on durability of pine needle and sisal fibre-reinforced concrete composites in a corrosive alkaline environment. The study finally illustrates the economic viability and environmental benefit of using natural fibre reinforced concrete.

1.6 Significance of the study

This study investigated the strength properties of concrete reinforced with pine needle and sisal fibres, leading to the emergence of sustainable innovation materials substances. The research findings enhance the understanding of fibre reinforced concrete and its potential applications and limitations in building construction. The use of natural fibres in concrete offers benefits such as reduced environmental impact and improved sustain-

ability. The study provides valuable insights in the strength properties of pine needle and sisal fibre concrete composites, informing the development of eco-friendly and environmental sensitive construction material. The findings have implications on for the construction industry, environmental agencies, researchers, policy makers, and communities seeking sustainable building solutions, advancing sustainable construction practices.

1.7 Scope of the study

1.7.1 Content scope

This research investigated the properties of concrete hybrids improved with pine needle and sisal fibres, focusing on their mechanical behaviour and durability. The study assessed the strength attributes of the composite material to determine its potential to stand against structural actions. The research examined the materials attributes to absorb water characteristics of the hybrid material to evaluate its resistance to water penetration and potential degradation. Furthermore, the study simulated an alkaline environment to understand the material's resistance alkaline conditions and degradation under alkaline surroundings, giving valuable information into its ability to perform well when used. In addition to the technical evaluation, the research conducted a cost-benefit analysis to compare the economic viability of using natural fibre reinforcement with traditional steel reinforcement. An environmental impact assessment was also performed to quantify the potential environmental benefits of using sustainable materials.

1.7.2 Geographical scope

The particular undertaking was limited to Kampala (see [Figure 1.1](#)), under the central region of the country where all materials were sourced and used to conduct the research. This area was considered because of its location with the presence of material and laboratory facilities, also, the resources limited the research to be undertaken in the up-country. The materials were then collected from within the central area of Uganda, Kampala, Kyambogo, Kireka and Wandegaya areas and all the laboratory tests done at the Central Materials Laboratory (CML, under Ministry of Works and Transport).

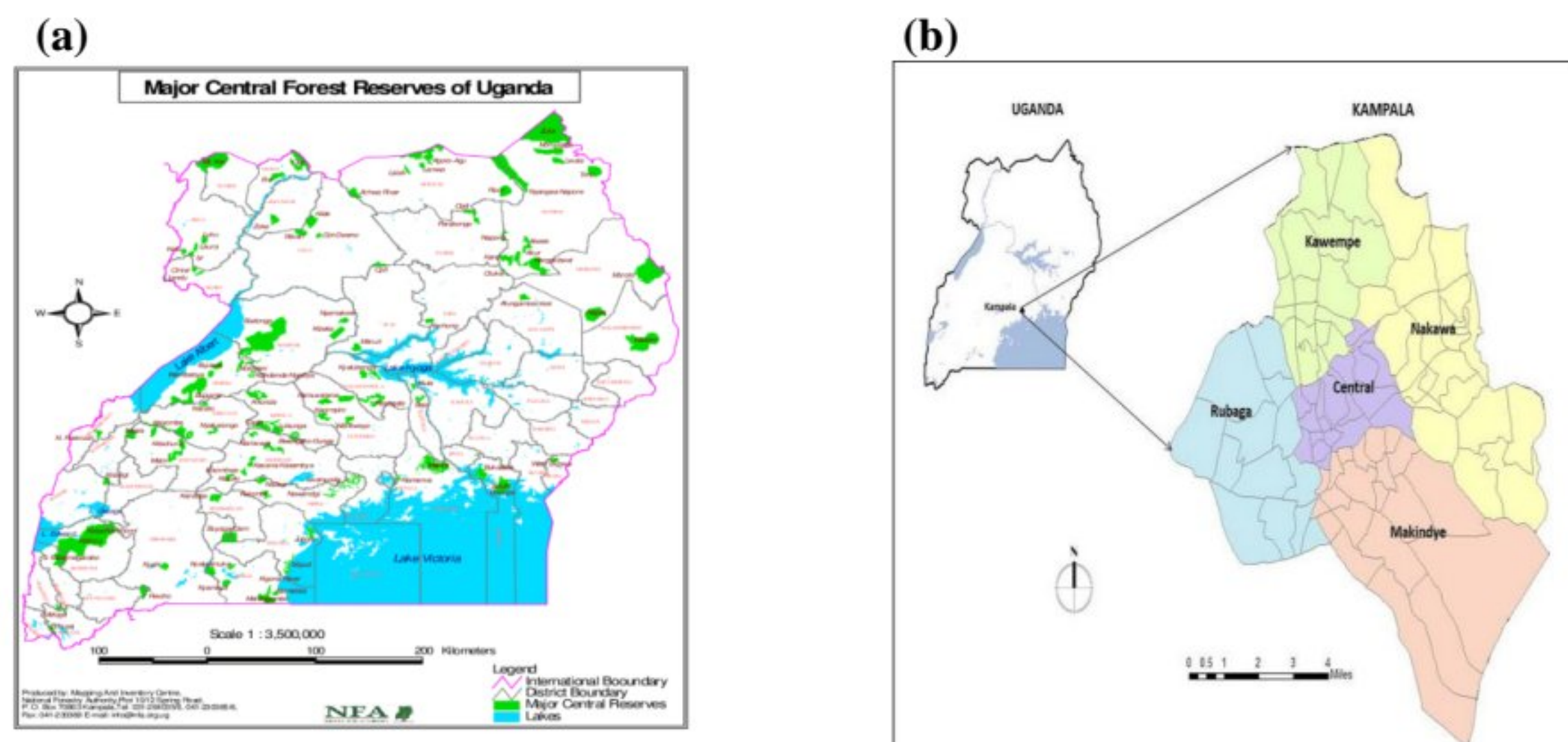


Figure 1.1 Geographical scope of the study area: (a) major central forest reserve of Uganda ([NFA, 2020](#)), and (b) the major divisions of Kampala

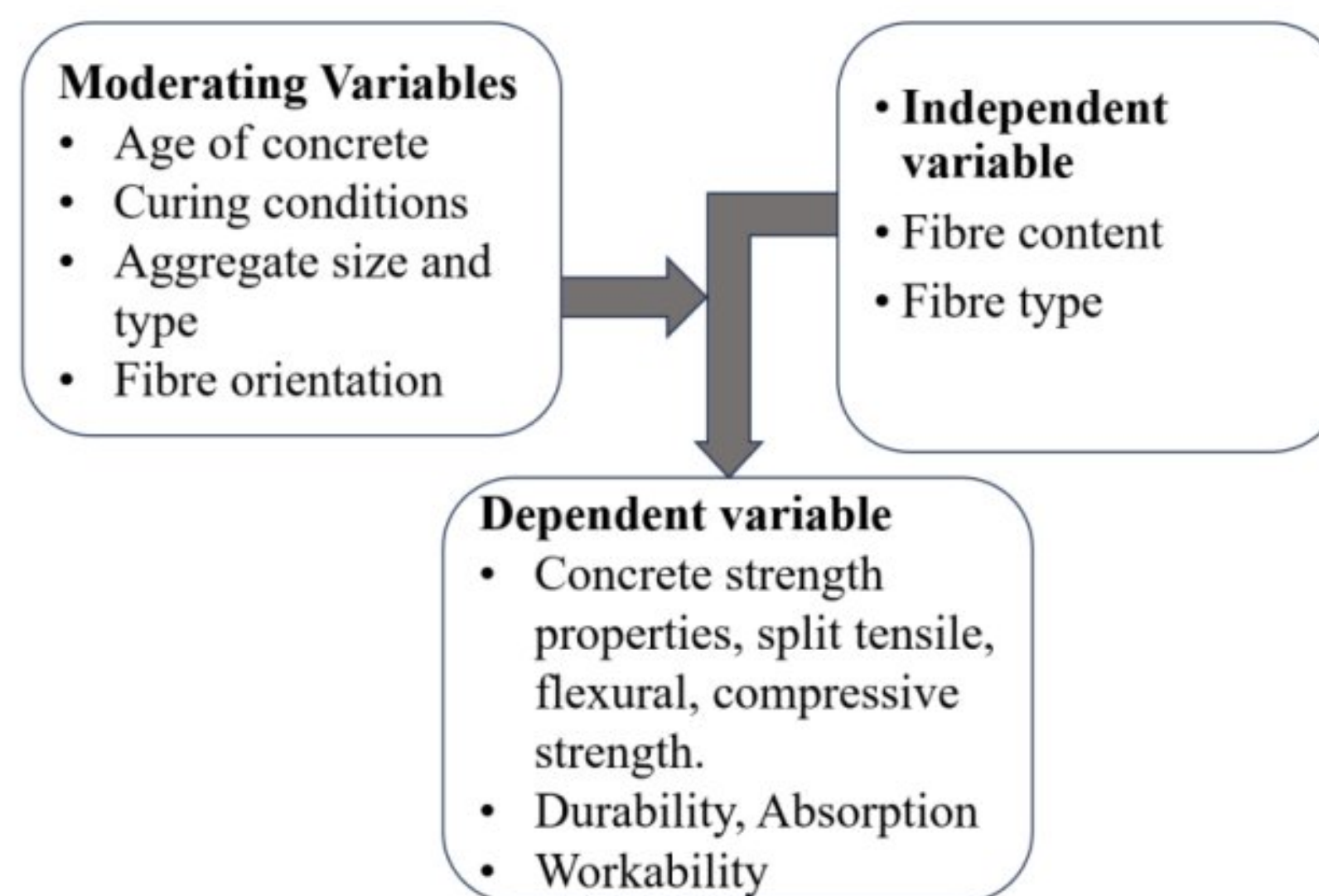
1.7.3 Time scope

The research was planned for at most 5 months, this includes material collection, sorting, sample fabrication, laboratory experiments (determination of fibre properties, optimal fibre composite proportions and concrete strength properties and durability). The theoretical review of this study was based on existing research in fibre-reinforced concrete composites, use of natural fibres in construction for sustainable development, with

emphasis on concrete strength property enhancement, fibre ratio proportions, suitability, cost benefit analysis and durability.

1.8 Conceptual framework

The concept building framework (see [Figure 1.2](#)) crystallises the study's core elements by visually mapping the relationships among key variables. In this figure, the independent variable is connected by an arrow to the dependent variable emphasizing the hypothesized cause-and-effect link. Additional arrows illustrate how a moderating factor helps to provide additional explanations. This diagram not only anchors the research questions but also provides a clear, visual foundation for the methodological design and data analysis that follow.



[Figure 1.2](#) Conceptual framework describing the study variables

1.9 Chapter summary

This chapter sets the need for exploration of sustainable construction materials to combat environmental concerns due to the high rates of demands for infrastructural development in developing countries, high carbon emission, high energy consumption, envi-

ronmental degradation. The chapter emphasizes on the ability of natural fibre-substances for innovation and creation of optimal building material-substances for the construction industry. It also states clearly the major objectives of the study including specific foci, justifying the need for the study and highlighting its significance and scope. The chapter lastly illustrates the conceptual framework pointing out the key variables and their impacts in the undertaking

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

The chase for eco-friendly construction material-substances has fuelled the search for innovative concrete material-composites, with a focus on integrating natural fibres and renewable materials to enhance concrete strength while minimizing environmental impact ([Paunov et al., 2025](#)). A variety of natural fibre-substances for example, coir fibres, jute, sisal fibres, banana fibres, pine needle fibre etc have presented themselves as better candidates due to their distinct attributes, abundance and potential to supplant synthetic fibres ([Thapliyal et al., 2023](#)). Pine needle, bamboo, jute like some other fibres, readily available and renewable, boast inherent characteristic that make them suitable for concrete strength property improvement ([Bi et al., 2024](#)).

Uganda recognises the significance of forests in driving socio-economic growth, with vision 2040 aiming to boost forest cover from 15% in 2010 to 24% by 2040 ([Uganda vision 2040, 2007](#)). The high aspect ratio, low density, moderate tensile strength, stiffness, and natural wax coating of natural fibres can enhance mechanical characteristics, energy consumption and longevity of concrete ([García et al., 2024](#)). This literature review aims to ensure a comprehensive assessment of the current situation of understanding on strength attributes of concrete reinforced with natural fibres. By synthesizing existing findings, experimental studies, literatures.

The innovative approach on natural fibre exploration for example pine needles, sisal fibres, jute, coir, bamboo fibres and many others in concrete composites is a rapidly evolving area of research, driven by the need for more sustainable and durable building materials ([Saini et al., 2024](#)). The theoretical review embarked on an in-depth explo-

ration of the synergistic potential of pine needle and sisal fibre composites in concrete, unlocking novel avenues for enhancing mechanical prowess and mitigating environmental concerns. The study aimed at consolidating current knowledge and gaps on the strength characteristics of concrete reinforced with natural fibres like pine needles, jute, bamboo, coir, sisal naturally existing fibres etc. This review aims at providing framework for this research, through provision of relevant concepts, theories, and to ensure that the hypothesis is grounded on existing knowledge.

The review objective involves critical synthesis of the existing knowledge based on mechanical attributes of NFRC, aimed at understanding the relationships between the type of fibre, and/or its content, proportion and properties on the strength attributes of concrete. Furthermore, the review presented herein focusses on identifying the knowledge lacunae and chart future research gaps and possible significant directions. This literature review is substantiated by the imperative and need for innovative, environmental-favouring building and construction materials-substances that harmonise strength, durability, and sustainability. By investigating the untapped potential of pine and sisal fibre composites, this review aimed to catalyse the development of sustainable concrete solutions, informing tomorrows understanding and practical material applications in the construction-building industry.

2.2. Natural Fibres

According to [Krifa and Gnanasekar \(2025\)](#), natural fibres have played a pivotal role in shaping human culture and daily life. For thousands of years, people have worn garments crafted from plant and animal fibres, which not only added aesthetic value but also provided protection against the environment. Beyond clothing, natural fibres have

been used in furniture, decorative items, and even structural components of buildings (Midani and Ali, 2025). In the 1960s, natural fibres were extensively used for many applications, including textiles and construction until the rise of synthetic materials in the 20th centuries significantly altered the landscape leading to the decline in the global market share of natural fibre from about 80% in 1960 to about 25% in the recent years (Julia, 2018).

With growing concerns, about the environmental issues, there is now a renewed interest in sustainable options and alternatives to sustainable practice and development including adoption of green practices, mindset change, effective waste management, in addition to sustainable materials (Umar et al., 2024). This can enhance reduced reliance on non-reusable resources and mitigate the issue of non-decomposable waste (Salmi, 2024). Harnessing natural fibres can significantly mitigate environmental impact of construction by reduction of carbon footprint (Sovbetov, 2025). As the world shifts towards a more protective-sustainable tomorrow, the adoption of natural-fibre substances in the building and construction industry is expected to gain momentum, driving innovation and growth in the sector.

2.2.1 Natural fibre classification

Fibre-substances are slender, reinforcing materials crafted from diverse substances like metals, polymers, carbon, glass, and natural elements which can be prepared in different forms and dimensions to suit specific uses (Geremew et al., 2021). Natural fibres are categorized considering their mode of origin, including plant-based, animal-derived, and mineral-based sources, with various types being explored for their potential use as reinforcements in bio-composites (NFA, 2020). Plant fibres can be further classified based

on the plant from which they are obtained, including bast fibres, leaf fibres' grass fibres and seed fibres, highlighting the diverse sources within plant-based materials ([Strategies, 2024](#)).

2.2.2 Application and uses of natural fibres

Bio-based materials, including plant and animal sources, give rise to natural fibres that offer a wide range of benefits and opportunities ([Josef, 2018](#)). These fibres, encompassing plant-based cellulosic fibres like cotton, jute, and sisal, pine needle as well as animal-derived protein fibres like wool and silk, are notable for their abundance and cost-effectiveness favouring biomass and biorefinery development ([Geoff, 2018](#)). As a result, they have emerged as viable alternatives for various industrial and commercial applications, including automotive interiors, building materials, packaging solutions, and furniture biomass design ([Dhaliwal, 2020](#)).

Furthermore, natural fibres are being increasingly utilized in insulation, geotextiles, and composite materials due to their unique properties and potential for sustainability ([Sapuan et al., 2022](#)). Ongoing research and development in fibre modification and treatment have significantly expanded the scope of natural fibre applications, paving the way for creating environmentally safe and friendly building-substances that can effectively replace synthetic materials ([Access, 2019](#)). The classification elaboration on some common natural fibres based on their origin is shown in [Figure 2.1](#). It is observed that natural fibres exhibit a broad spectrum of properties, and understanding their classification is key to unlock their potential. Furthermore, [Figure 2.1](#) categorises natural fibres offering insights into their types and subcategories. This classification high-

lights the diverse sources of natural fibres. Each of them having distinct properties and applications.

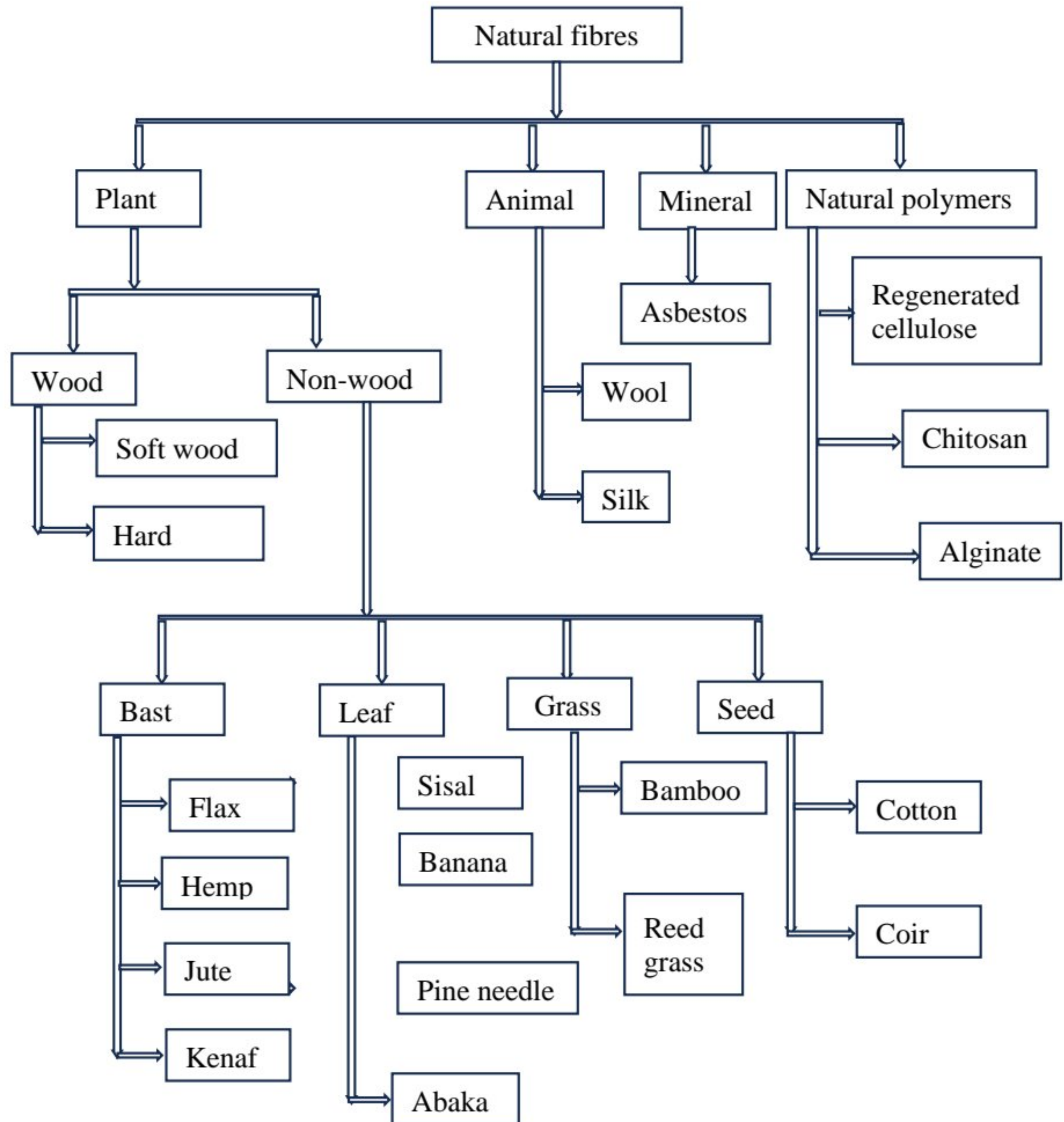


Figure 2.1 Classification of some common fibres by origin (Khan et al., 2022).

2.3. Physical, mechanical characteristics of pine needle and sisal fibres

Sisal fibres can be defined as naturally existing tinny-fibres obtained from the parts of agave sisalana plant through decortication; they are commonly found in tropical and

subtropical areas. Pine needle fibres are abundant in pine forests globally, often collected from logging and forestry waste. The harvesting involves gathering fallen needles and processing them, cleaning, cutting into required length. The following are properties of pine needles and sisal fibre composites. The makeup of natural fibres consists of cellulose microfibrils embedded in a matrix of amorphous lignin and hemicellulose. The lignocellulosic cell wall is viewed as a naturally existing structure featuring spirally arranged cellulose microfibrils amidst various biochemical compounds (Geremew et al., 2021). The basic chemical structure of plant fibre has components of lignocellulose (cellulose, hemicellulose and lignin). Table 2.1 up to Table 2.3 explains more natural fibre properties.

Table 2.1 Properties of sisal fibres (Okeola et al., 2018)

Fibre Property	Result
Fibre diameter	0.10-0.13
Aspect ratio	230-300
Tensile strength	343-399MPa
Tensile modulus	10.2-14.66
Shape	Straight
Colour	Creamy white
Density	0.113g/cm ³
Water absorption	43.58%
Specific gravity	0.73

Table 2.2 Chemical properties of Sisal fibres ([Benítez-Guerrero et al., 2017](#))

Component	Composition range (wt.%)
Cellulose	43-88
Hemicellulose	10-15
Lignin	4-20
Pectin	0.8-10
Water soluble	1-4
Fat and wax	0.15-2
Moisture	10-22

Table 2.3 Material properties of pine needle fibres ([Tolga Cogurcu, 2022](#))

Property	Values
Weibull modulus	5.07
PH	5.92
Lignin	10-16
Holocellulose	79-73
Cellulose	47-57
Tensile strength MPa	36.72
Threshold stress MPa	36.94

2.4. Advantages and disadvantages of pine needle and sisal fibre

An experimental investigation conducted by [Kurpińska and Mazur et al. \(2022\)](#) on the impact of natural fibre properties on the concrete strength characteristics the study examined Sisal fibre, Jute fibre, Bamboo fibre, Ramie and Cotton fibres. Results indicated that the fibres modified the mixtures' consistency by up to 15%. The composites strength test revealed that strength variation of positive and negative 8%, contingent upon fibre type. Furthermore, composition chemically, and length, diameter of these fibrous materials significantly impacted composites shrinkage ([Kurpińska and Mazur et](#)

al., 2022). The advantage of these fibres include abundance, renewability, potential to improve concrete strength properties with reduced crack propagation and reduced shrinkage. However, the fibres have drawbacks, including high water absorption, may degrade over time, and may require chemical treatment over time.

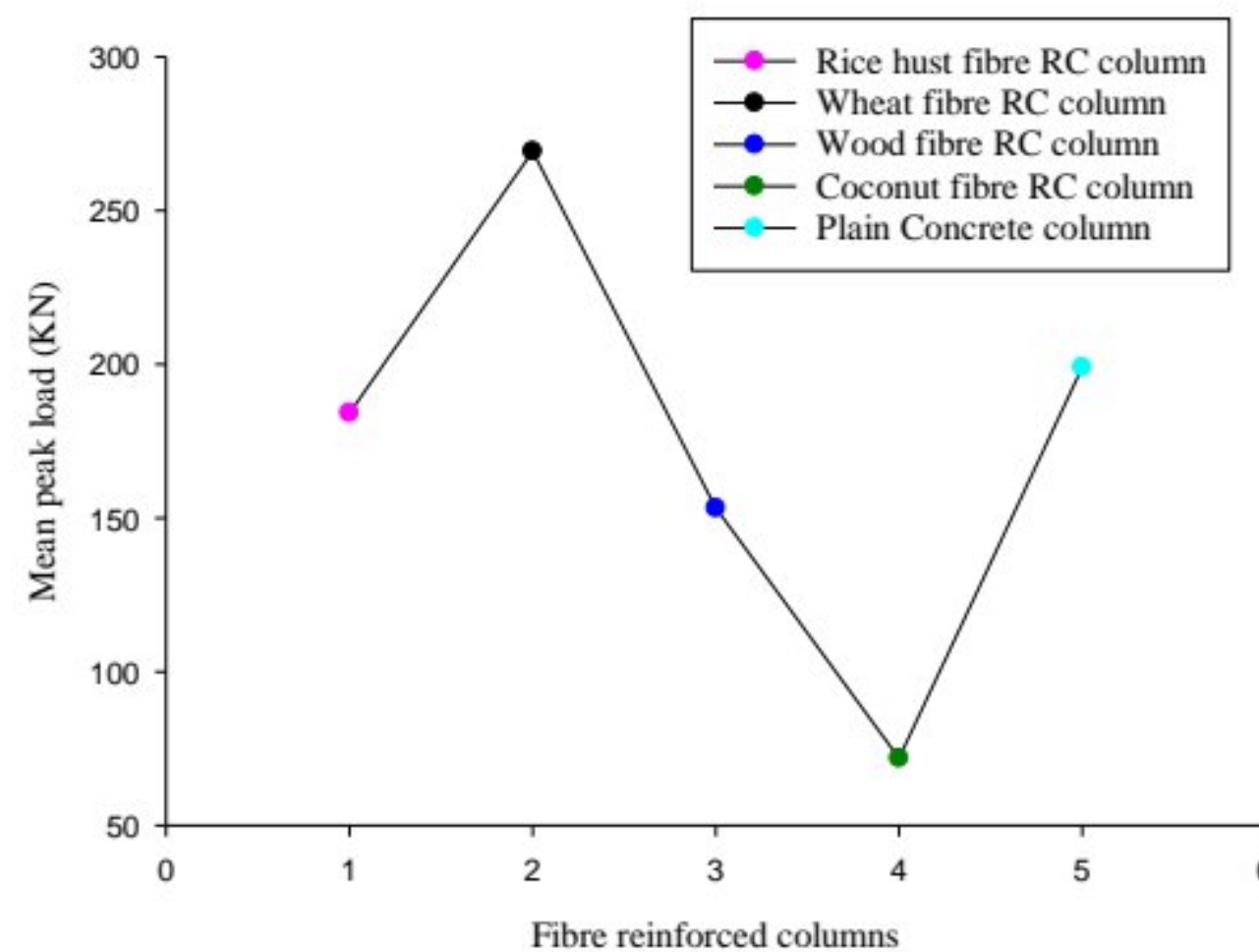
2.5. The impact of fibre proportions on concrete strength properties

According to Rocha et al. (2022), the final characteristics of hardened cement composites are induced by a number of key factors, including the proportion of a particular fibre, its type, attributes, length and treatment. These variables impact the interaction between the fibre and matrix, affecting the overall composite's performance (Li et al., 2025). The efficiency of the bond between the fibre concrete material is crucial, with factors such as fibre roughness, length, diameter playing a significant role. However, a strong bond is not solely dependent on these factors. Rocha et al. (2022) added that the attraction between the matrix and the component of the reinforcement substance is also essential as it enables the transfer of loads from the matrix into the reinforcement.

A weak link can lead to a non-complete load shift or movement, resulting in the reinforcement being pulled out and compromising the composites strength (Fu et al., 2024). Conversely, a strong interface ensures effective load transfer, contributing to enhanced composite's performance. The proportion and length of fibres used as reinforcement materials in concrete composites mixtures impact on its workability. This suggests that careful considerations of the fibre properties is essential to achieve optimal concrete performance (Geremew et al., 2025a). The mixture and proportions of fibres in the composite predicts the mechanical characteristics of the hybrid material, the estimation of the optimal fibre content and distribution is critical (Başürücü et al., 2022). Key

considerations include fibre volume fraction: optimal fibre content for enhanced strength concrete properties. Moreover, the fibre length and distribution effects on strength properties, matrix properties, concrete properties influence the composite's strength is detailed in the study by [Hamada et al. \(2023\)](#).

Experimental studies done by on reinforced concrete columns with various fibres (e.g., coconut, wheat, rice husks, and wood fibres) showed that the strength of the columns improved with fibre varied between 0.76 and 1.67 times in comparison with the plain concrete columns with coconut fibres showing the poorest results as shown in [Figure 2.2](#).



[Figure 2.2](#) Mean peak load for natural fibre reinforced concrete columns, [Kumarasamy and Gebreyowhanse \(2020\)](#)

Recent research carried by [Kumarasamy and Gebreyowhanse \(2020\)](#) investigated the mechanical attributes of Bamboo FRC, focusing on compressive, flexural, and split tensile strength at different fibre proportions of 0, 0.1, 0.2, 0.5, 1, 1.5, 2 and 2.5%, proportions of 0.1%, 0.2% and 0.5% of each fibre and tests conducted in 7, 14, and 26 days after proper curing of the samples. The study revealed that incorporating Bamboo fibre

up to 2% enhanced the strength properties with a slight decline beyond this optimal dosage. Notably, the flexural strength results indicated improved bending resistance with more added fibre contents up to 2%, followed by a marginal decrease. The findings suggest that Bamboo Fibre-reinforced concrete outperforms conventional concrete, offering enhanced strength characteristics as shown in [Figure 2.3](#), [Figure 2.4](#) and [Figure 2.5](#).

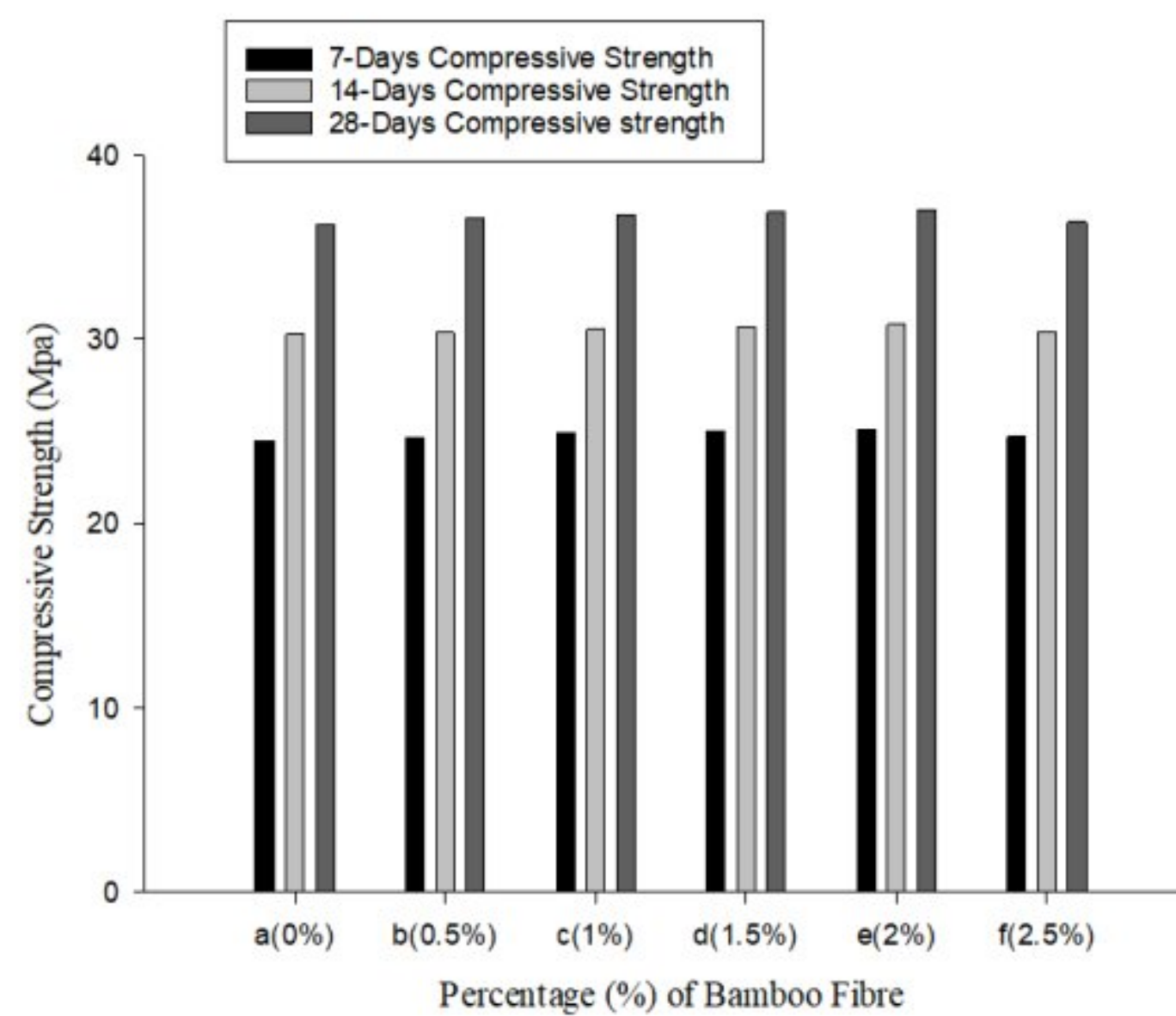


Figure 2.3 Compressive strength of Bamboo reinforced concrete ([Kumarasamy, 2020](#)).

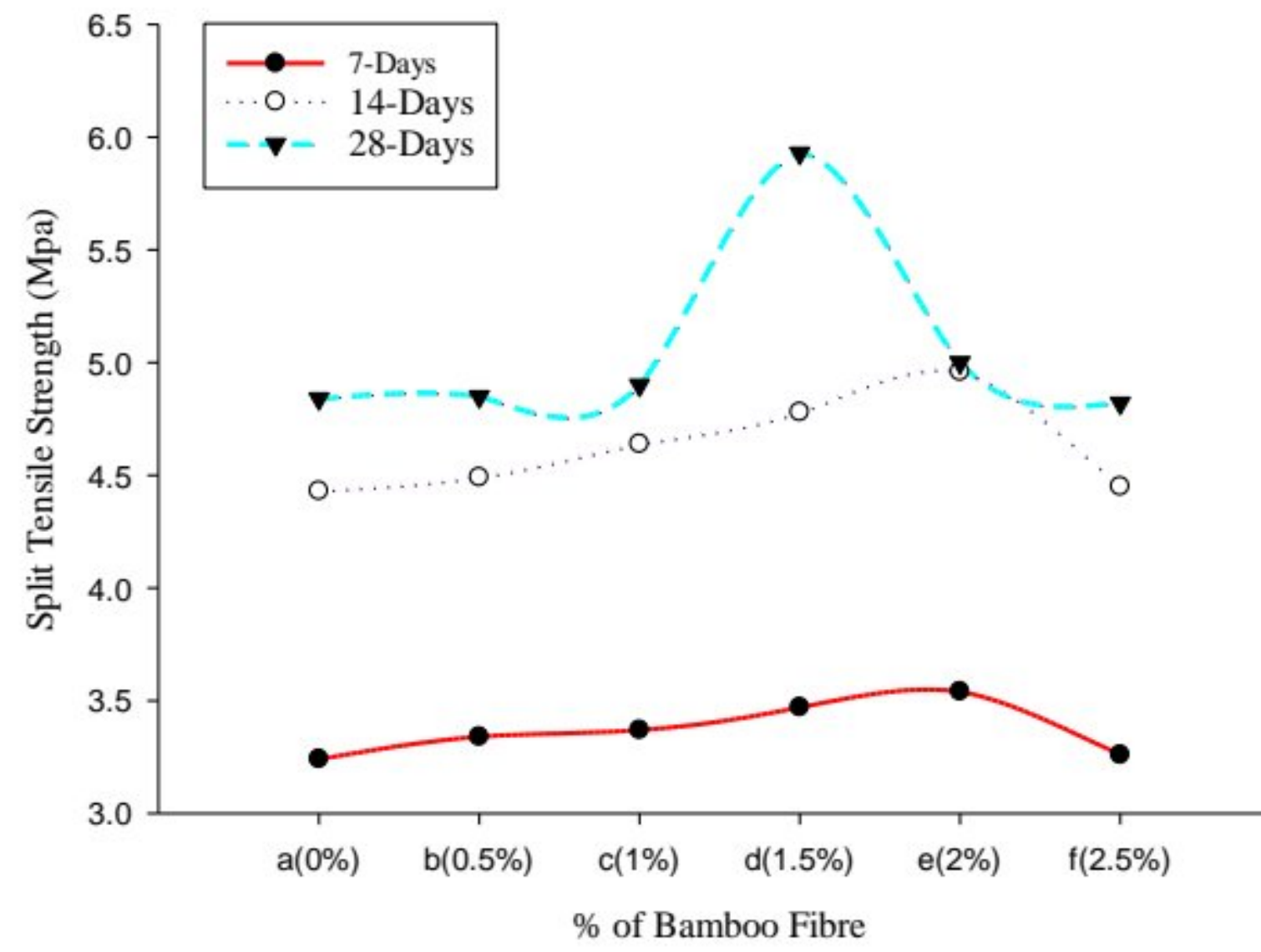


Figure 2.4 Split tensile strength of Bamboo reinforced concrete (Gebreyowhanse, 2020).

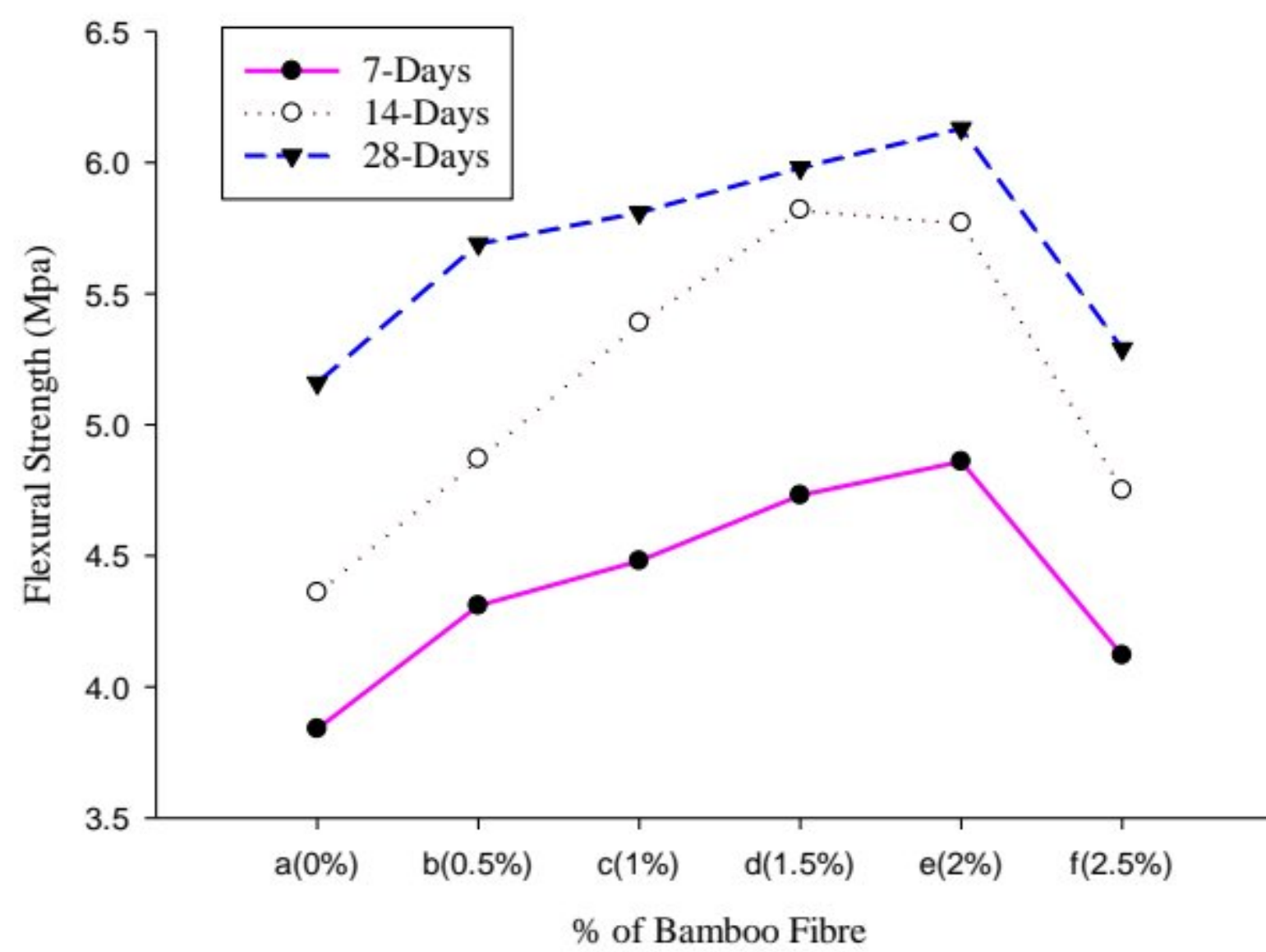


Figure 2.5 Flexural strength of bamboo fibre reinforced concrete (Gebreyowhanse, 2020).

Ahmed et al. (2024) carried out an experiment on the mechanical understanding of concrete incorporating Basalt fibres at varying concentrations of 0.5%, 1.0% and 1.5%. The stress strain response-curve showed the same initial stress behaviour across all samples, with the 1.0% Basalt Fibre Reinforced concrete showed a steeper curve

stretching up to the highest stress point. Notable, the 0.5% Basalt Fibre Reinforced Concrete Sample demonstrated greater deformability before it reached the highest stress value in comparison to other samples.

Additionally, an addition of fibre dosage corresponded to a rise in ultimate strain, suggesting improved performance in withstanding deformations beyond initial cracking. Yusra et al. (2024) executed an experimental study on the effect of Rattan and bamboo fibres on the split tensile strength of concrete the results were as shown on Figure 2.6. The results revealed an average strength of 2.73 MPa for fibre free sample after 28 days.

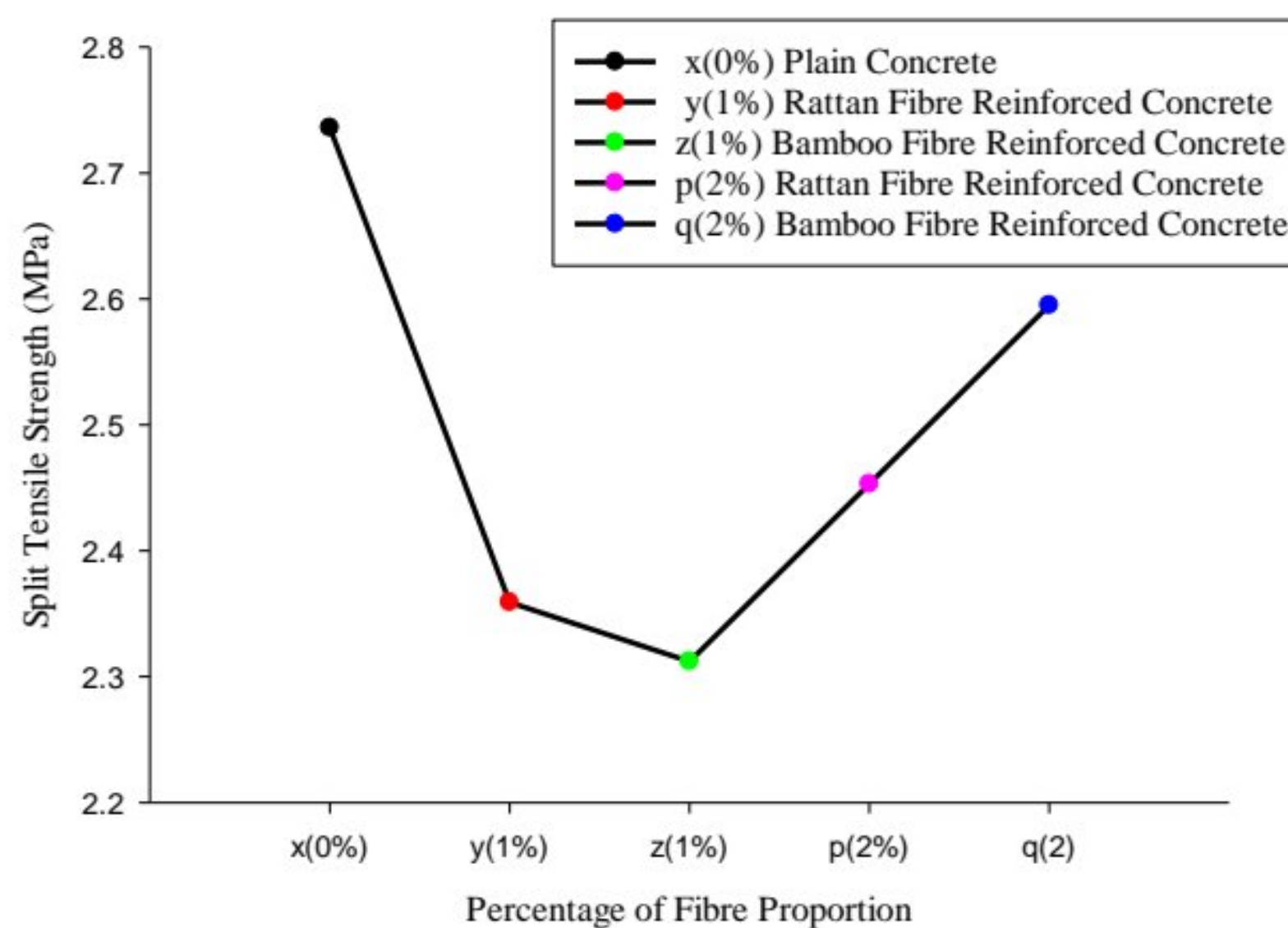


Figure 2.6 Split tensile strength of concrete incorporating rattan and bamboo for varying fibre contents (Yusra et al., 2024).

In contrast, fibre reinforced samples showed varying strength, with 2.0% Rattan fibre reinforced sample exhibiting the largest average of tensile strength of 2,595 MPa. Conversely, the 1% Bamboo fibre variant yielded the lowest average strength of 2.312 MPa. Yusra et al. (2024) conducted a compressive strength teste on Rattan and Bamboo

Fibre reinforced concrete revealed that the fibre free samples achieved an average strength of 26.29 MPa after 28 days. Among the fibre reinforced samples, the 1.5% Bamboo fibre variant yielded the largest average compressive strength of 24.74 N/mm². However, this was still lower than the control experiment value. Notably the 0.5% Rattan fibre reinforced concrete sample resulted in the lowest strength as shown in Figure 2.7.

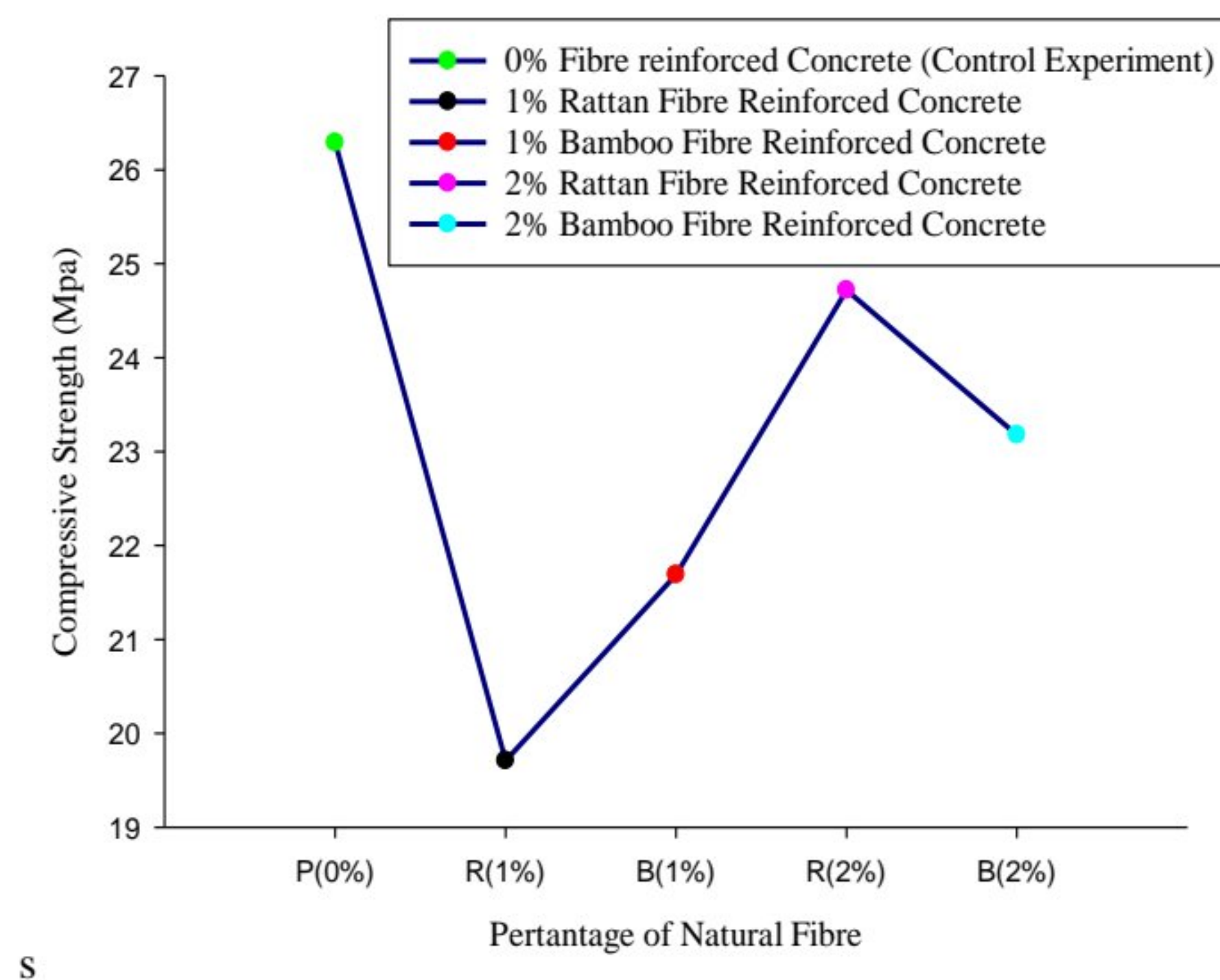


Figure 2.7 Compressive strength of concrete with varying Rattan and Bamboo fibre contents (Yusra et al., 2024).

2.6. Natural fibre reinforced concrete

According to Sayyad and Sayyad (2023), fibre reinforced concrete is a concrete containing fibrous materials meant to improve its strength properties in this case, the fibres used are natural fibres harvested from natural vegetation. When the concrete strength properties are improved by use of natural fibres, the composite formed is Natural Fibre

Reinforced Concrete (NFRC) ([Hait et al., 2024](#)). Fibres used in FRC include sisal, jute, glass fibres, synthetic fibres, steel fibres, randomly distributed in concrete. Most of the fibres (e.g. jute, sisal, hemp, banana fibres) help reduce crack propagation caused by plastic reduction in volume loss of water, they also reduce bleeding, permeability hence improving abrasion, and concrete resistance ([Yusra et al., 2024](#)). According to [Mahmoud \(2024\)](#), FRC has a great potential for its applications, technology advancement, improving stability of structures, especially in mass concrete structures, pre-cast concrete products ([Tjcd et al., 2022](#)), airport runways, pavements, and bridge decks ([Cho et al., 2024](#)).

Most researchers have tried some fibres especially steel fibres, and natural fibres which has given a promise for commercial production and better environment in the next years to come ([Karim et al., 2021](#)). The consideration of sustainable material practices in the building and construction sector has led to reduction carbon weight hence environmental safety and protection ([Zamathula et al., 2024](#)). In addition, before the emergence of concrete, a natural fibre was used in combination with clay mud to construct buildings with thicker walls, which exhibited warmer characteristics during winter and cooler in summer, in this form, fibre played a great role in crack resistance including improvement in bonding character ([Cho et al., 2024](#)).

The integration, innovation of sustainable, natural materials like fibres and recycled materials has led to emergence of low cost, and ecofriendly materials ([Manu, 2024](#)). By integrating natural fibres with concrete, NFRC leverages the strength of both components, yielding enhanced mechanical properties and reduced environmental footprint. Research done by [Hamada et al. \(2023\)](#) can significantly augment concrete's ten-

sile, flexural and compressive strength. Another ventured in by [Yusra et al. \(2024\)](#) revealed significant concrete strength property improvement. Furthermore, demonstrated that incorporating natural fibres into concrete enhances its durability, minimizing degradation, since the fibre substances enhance the mechanical behavioural attributes of concrete. Research findings indicate that incorporating jute fibres into concrete enhances its bonding with cement and aggregate, resulting in improved compressive strength at both early 7-days and 28-day stages.

The strength enhancement is more pronounced with increased jute fibre content. However, inhomogeneity and adverse effects on strength, likely due to fibre clustering or balling ([Shrestha et al., 2024](#)). [Figure 2.8](#) represents results out of the study carried out by ([Wilson et al., 2025](#)), the findings of this study indicate that incorporating jute fibres at a 0.5% volume fraction significantly enhances the concrete's compressive behavioural characteristic, outperforming plain concrete, with a 10.3 % notable concrete increase.

[Shukla \(2013\)](#) explored that many fibres including natural fibres have been innovatively adopted in the creation of many infrastructural-building materials including roofing sheets and house structural components. He adds that fibres like coir, bamboo, synthetic fibres, straw have been incorporated in the brick manufacturing process. The key concept is that the deformation of the composite's matrix will transfer all the stresses to the fibres, this has been evident in asbestos sheets which have been in use for a long time zone.

According to [Sethunarayanan et al. \(2007\)](#), there has been a considerable research on steel fibre Cementious concrete composites including concrete elements, and

so few trials have been made on Natural Fibres. He recommended that to achieve some strength, the moisture content is vital in the natural fibre, however, when the fibres dry in the composite, they become brittle, hence losing their tensile behaviour. A major disadvantage of natural fibres. However, the study recommended that more investigations be done on natural fibres to popularize them. The investigation carried by [Gujre et al. \(2023\)](#), showed that the use of agricultural products like NF in Cementious composites improves the crack resistance, decreases the shrinkage and cracking in the cement matrices. [Figure 2.8](#) elaborates the interaction correlation between jute fibre contents and concrete compressive strength.

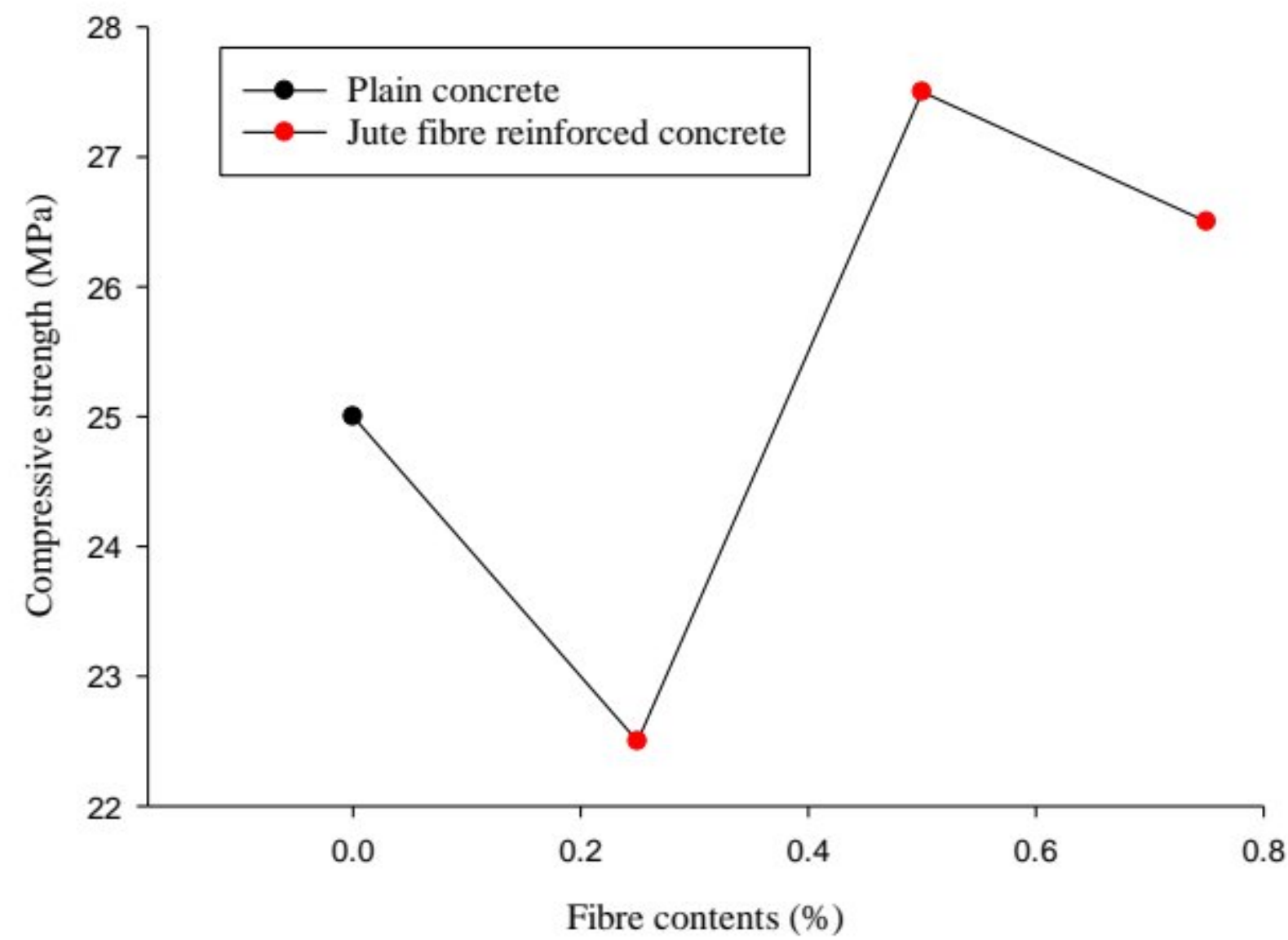


Figure 2.8 Compressive Strength of Concrete with Varying Jute Fibre Proportions
([Shrestha et al., 2024](#)).

In addition, the workability of the concrete composite is adversely affected on addition of fibres, however, fracture and toughness characteristics are enhanced. The compressive behaviour characteristic of the concrete composite is not varied so much up to certain contents, however, the tensile strength of the NFRC is significantly affected.

This gives a foundation for the exploitation of natural fibres as sustainable construction materials.

Naturally available eco-friendly existing materials for example wood, bamboo, sisal, palm, pine needle, straw and other locally available fibres can be used as substitutes for non-decomposable and non-reusable materials ([Geetha and Vijayalakshmi, 2023](#)). Fibres like Kapok were used to enhance the flexural strength toughness in bio-lime based mortar and in the manufacture of eco-compatible prefabricated bricks. In conclusion, NFRC exhibits remarkable potential as a sustainable construction material and so further research is required to fully elucidate its properties and more applications.

2.7. Durability, economic viability and environmental benefit FRC

Research finding indicate that durability of especially treated hybrid natural fibre reinforced concrete is significantly improved compared to plain concrete though with challenges in considerable variability in physical and mechanical characteristics ([Saini et al., 2024](#)). The failure modes of fibre reinforced concrete differ substantially from those of neat concrete, highlighting the benefits of fibre RC ([Geremew et al., 2025a](#)).

The experimental study confirms that naturally treated fibres can be effectively put for as improvement materials in concrete components, offering promise in durability through improved concrete properties. [Salmi \(2024\)](#) conducted an experiment on enhanced longevity safety and sustainability in concrete-materials with FRC composites, the study observed a significant reduction in crack propagation, attributed to self-healing mechanism. This suggests that the fibre reinforced concrete can effectively mitigate the spread of cracks leading to improved durability and longevity. The results also showed evidence on enhanced overall stability and robustness in the fibre reinforced

concrete. This enhancement in structural integrity can be linked to the fibre's potential to absorb and distribute loads, reducing the likelihood of catastrophic failures.

In addition, [Salmi \(2024\)](#) conducted an analytical experimental research on enhancing long life and sustainability in concrete with fibre improved hybrid and concluded that a notable 40% decrease in crack width observed in self-healing fibre-reinforced concrete. The findings in this research also improved durability since there was a notable increase of 40% in compressive strength, evidenced in improved integrity of concrete compared to the control experiment. The findings conclude that the use of fibres to improve the strength properties of concrete can lead to longer-lasting structures, reduced maintenance needs and improved overall performance and durability ([Sayyad and Sayyad, 2023](#)). The findings of the studies conducted by [Hassan and Saeed \(2024\)](#) showed that the utilization of fibres in concrete composites can lead to improved durability and reduced maintenance needs.

The comparative study conducted by [Aakash \(2024\)](#) demonstrated that mixtures with higher fibre volume percentages exhibit higher air content compared to those with lower fibre volume fraction. In conclusion, a thorough comparison of conventional concrete beams with natural fibre-reinforced concrete (NFRC) beams has provided important new information about the structural performance of each material. In comparison to conventional beams, NFRC beams have a significantly larger ultimate load capacity and better deflection characteristics, according to experimental testing conducted under 2-point loading. This result emphasizes how natural fibre reinforcement can improve the mechanical qualities of concrete constructions hence higher durability properties compared to the plain concrete.

This aspect can be ascribed to the challenges in consolidating fibre-reinforced mixtures, resulting in entrapped air and more challenges ([Islam et al., 2024](#)). The results indicated that augmenting fibre content reduces the loss of tensile and compressive strength, as well as weight loss. This implies that fibre play a vital role in enhancing the durability of concrete composites. [Geremew et al. \(2025a\)](#) experimentally investigated the mechanical characteristics and longevity of the hybrid naturally fibred RC using wheat straw and bamboo fibres as sustainable reinforcements in concrete for pavement application.

By incorporating 0.1% wheat straw fibres and varying baboo fibre contents to (0.5%, 1%, 1.5% by weight of cement) with fibre length of 30mm, 45mm, and 60mm, the study revealed noticeable enhancements in mechanical properties, including significant enhancement of the strength of compressive at 7, 28, and 56 days. Furthermore, the hybrid fibre reinforcement substantially improved the split tensile, and flexural strength, plus longevity characteristics of the concrete hybrid. The result also indicated a shift in the failure mechanism from its brittle nature to its ductility form and increased energy absorption ability.

More experimental studies conducted by [Jamshaid et al. \(2023\)](#) explored the durability and ageing characteristics of various natural fibres including jute, sugarcane, coconut, sisal and basalt when used as reinforcement in concrete. Through accelerated ageing tests, fibres were exposed to alkaline environments with varying pH levels and solution concentrations. The findings revealed that jute fibres exhibited the highest weight loss percentage in concrete composites, whereas basalt fibres showed minimal degradation. The ageing process significantly impacted the strength of jute fibres, while

sisal fibres demonstrated increased tenacity due to fibrillation. Notably, basalt fibres exhibited superior fibre pullouts strength, indicating excellent adhesion with cement. This study provided insights on durability, ageing and performance of natural fibres when used in concrete as reinforcements and exposed to different environmental conditions.

The economic feasibility of incorporating natural fibres into concrete is a notable benefit, especially utilizing locally sourced and renewable materials like sisal, jute, and hemp, construction costs can be significantly reduced ([Sapuan et al., 2022](#)). These natural fibres are not only inexpensive but also abundant, making them an attractive alternative to traditional reinforcement materials ([Girijappa et al., 2019](#)). Research has shown that the incorporation of naturally existing fibre-substances can result into substantial savings in costs, making concrete a more viable option for construction projects. Furthermore, natural fibre-reinforced concrete may reduce the need for steel reinforcement, which can be costly and prone to corrosion ([Pham, 2025](#)).

The reduced costs associated with natural fibre-RC is possibly attributed to the low cost of the fibres themselves, as well as the potential for local sourcing, which minimizes transportation costs ([Abdalla et al., 2023](#)). Additionally, the use of natural fibres may eliminate the need for specialized labour and equipment, resulting in further cost savings. This makes natural fibre-reinforced concrete an appealing option for construction projects, particularly in locations where resources are inadequate.

The incorporation of the biodegradable and renewable materials reduces the environmental impact of concrete production ([Impact, 2024](#)). Moreover, the inclusion of natural fibre-substances into use can reduce the amount of cement required, which is a

key contributor to dangerous gas emissions. Studies have highlighted the importance of reducing cement consumption in concrete production to mitigate climate change ([Berger and Pfeifer, 2024](#)).

The repurposing of agricultural waste as reinforcement materials in concrete can also contribute to a reduction in waste management issues. By utilizing natural fibres, the building industry can possibly decrease its dependence onto synthetic substances and reduce its environmental footprint ([Forum and Nations, 2024](#)). This approach promotes sustainable construction practices and supports the development of environmentally friendly infrastructure.

The purposeful put into use of locally found natural fibre-substances may have a constructive effect on the local economies and markets; by creating new opportunities for farmers and rural communities, natural fibre-reinforced concrete can support local economic development and promote sustainable agriculture practices ([Kocira and Staniak, 2025](#)). Overall, the economic and environmental benefits of natural fibre-reinforced concrete make it a promising option for construction projects, and its adoption can contribute to a more sustainable future.

Even though the natural fibres as reinforcement composite materials are susceptible to decomposition or biodegradation because of several conditions or factors, starting from photochemical to biological reactions, research considering these factors remains limited in literature ([Ramful Raviduth, 2024](#)). The degradation of the fibre interface besides its interaction with the strength of NFRC, the interfacial strength imparts a key significant influence in the biodegradability, hence impacting on the durability of the NFRC. The results recorded in this study are provided in [Table 2.4](#) below.

Table 2.4 Estimated fibre degradation of typical biodegradable composite materials over 100-day period ([Ramful Raviduth, 2024](#))

Reinforcement fibre	Weight Percentage composition	Estimated degradation rate over 100-day period
Durian skin fibre	PLA+30 wt. % composite	7.00
Pineapple leaf fibre	PLA +9 wt.% + 2 wt.% PLAF	12.40
Elephant grass	PLA +25 wt.% elephant grass composite	18.12
Starch	PLA +90 wt.% starch composite	>100
Luffa fibre	PHB +50 wt.% LF-composite	29.17
Hemp fibre	PHB +20 wt.% hemp	>100
Jute fibre	PHB +20 WT.% JUTE+ 5WT % PHB-g-MA	>100

In the previous research findings, the decomposition of the fibre matrix was recorded to happen under surrounding aging hence significantly causing debonding between the fibre and the Cementitious matrix. in addition, in interfacial debonding is thought to have been caused by the penetration of water molecules into the NFRC which later on forms blisters. It should also be noted that the nature and polarity of the NF, impact greatly on the bonding character of the natural fibres.

2.8. Failure, behaviour and applications of natural FRC composites

According to [Seeboo and Proag \(2021\)](#), the limitations of synthetic fibres and drawbacks of plain fibre-substances have geared into key advancements in the use of NFC. different fibre methods of extraction have been put forth, tailored to the attributes of different fibre. However, research has highlighted fibre agglomeration and hydrophilicity

as potential drawbacks to achieving high strength natural fibre RC with recorded compressive strength fall of 75.1% and 90.1% compared to neat concrete in different volume portions. Moreover, the durability of natural fibre reinforced concrete remains a major concern due to their susceptibility to degradation in highly alkaline environments, where they struggle to resist hydration products, leading to inevitable fibre degradation as the concrete ages ([Islam et al., 2024](#)).

An experimental study conducted by [Series \(2021\)](#) investigating the load bearing capacity of a naturally fibre reinforced columns revealed that the addition of superplasticizers enhanced their performance, with rice husk fibres exhibiting the most significant improvement. Although the columns ultimately failed to compressive loading. The failure was observed as the split cracks developed between the fibres and the concrete, with coconut exhibiting lower ductility compared to other fibres, that's to say rice husks, wheat husks and wood fibre.

[Kouta et al. \(2023\)](#) carried an experimental investigation exploring the contribution of flax-fibres on mechanical characteristics of the earth concrete, utilizing Digital Image Correlation (DIC) and Acoustic Emission (AE) techniques to analyse fracture behaviour and damage mechanisms. Prismatic specimens with varying fibre contents (0%, 0.3%, and 0.6%) and length (12mm, 24mm and 50mm) were put to the tests of three bending experiment. The findings indicated that increased fibre content and length enhanced Acoustic Emission activity and fracture energy while the fibre's bridging effect improved crack opening resistance, ultimately demonstrating the capability of natural fibre-substances to improve ductility in natural fibre reinforced concrete composites.

2.8.1 Applications of natural fibre reinforced concrete

Natural fibre composites demonstrate an extensive array of applications across multiple industries, including construction, aerospace, and sports ([Di Sarno et al., 2024](#)). Featuring products such as partition boards, ceilings, watercrafts, office supplies, and industrial equipment, with significant focus on non-structural indoor elements due to their susceptibility to environmental degradation. The increasing need for environmentally friendly buildings that prioritise ecological awareness, functionality, and occupant health has driven the adoption bio-composites as crucial sustainable building materials ([OBS-Sustainable-Construction-Barometer-2025](#)). These bio-composites are classified into two main categories: structural bio-composites encompassing bridges, and roof framework and non-structural bio-composites including windows, exterior facades, and composite panels ([Geremew et al., 2021](#)).

The importance of NFRC composite such as exceptional stiffness-to-weight ratio, reduced weight, and bio-degradability make them well-suited for various construction applications ([Raghoo et al., 2021](#)). More over thin-walled components fabricated from sisal fibre reinforced composites display high tensile and compressive strength, broadening their application range to structural building components, permanent formwork, storage tanks, building facades, expansive roofing systems, and retrofitting existing structures enhancing circular economy and sustainability ([Umar et al., 2024](#)). The applications of most natural fibres are laid down in [Table 2.5](#).

Table 2.5 Applications of bio-composites in construction works ([Geremew et al., 2021](#)).

Parts	Material used
Panels	Sisal Jute Sandwich hybrids
Panel roofs and doors	Bamboo mat hybrids
Furniture	Jute Coir hybrids
Cupboards	Door frames of jute pultruded, Medium-density door hybrids
Wardrobes	NFR boards

Natural fibre reinforced concrete products such as light weight sheets and boards, are perfectly suited for roofing, ceilings, and walls in affordable or low-cost housing projects for urban settlements. Additionally, natural fibre improved concrete improves static and dynamic tensile strength, energy absorption capacity, and fatigue durability, rendering it suitable for airfield overlays, pavements, refractory coatings, and other specialized applications ([OBS-Sustainable-Construction-Barometer, 2025](#)). The homogenous distribution of fibres in NFRC ensures isotropic properties, facilitating its use in manufacturing pre-cast elements like pipes, fencing posts, watercraft, beams, stair treads, sanitary inspection chambers, concrete barriers and roofing panels among others.

2.9 Literature review summary and research gap

The mix of naturally existing fibres into concrete has been shown to offer several benefits, including improved ductility, energy absorption, and resistance to cracking. These benefits can be attributed to the distinct attributes of NF, such as their high cellulose content, low density, and ability to form strong bonds with the concrete matrix ([Laouici et al., 2024](#)). Various natural fibre like, sisal, pine needle, hemp, bamboo, flax, and jute, have been explored for their potential to improve the mechanical characteristics of concrete.

Some research studies have proven that the performance of NFRC is influenced by different factors, for example dosage, fibre orientation and length, the interface bonding between the fibre matrix and concrete ([Raghoo et al., 2021](#)). The optimal fibre content and length may vary majorly depending on the intended application and desired attributes of the composite. Say, shorter fibres may be more effective in improving the tensile strength of concrete, while longer fibres may be more beneficial for enhancing its toughness and ductility ([Wang et al., 2024](#)). Despite the advancing research body on natural fibre RC, a significant knowledge gap exists regarding synergistic effects of combining fibres, e.g. pine needles and sisal fibres in concrete composites as hybrids, this can enhance better properties ([Prem Kumar et al., 2023](#)).

The literature synthesis revealed that further studies are needed to investigate durability of natural fibre reinforced composites with more studies on hybrid fibres, orientation and dispersion of fibres in natural fibre-RC including the interaction of fibres with the concrete matrix ([Pham, 2025](#)). Some studies reveal need for more research on the contribution of the surrounding factors, say temperature, alkaline environments, UV exposure, humidity, treatments on the performance of these NFRC composites ([Rocha et al., 2022](#)). Additionally, there is a need to develop more optimized mix designs for different fibre types and also do stress loading of the NFRC to ascertain its loading capacity ([Gao et al., 2025](#)).

[Salmi \(2024\)](#) conducted analytical experimental research on enhancing durability with fibre reinforced composites and concluded that a notable 40% decrease in crack width observed in self-healing fibre-reinforced concrete. The findings in this research also improved durability since there was a notable increase of 40% in compressive

strength, evidenced in improved integrity of concrete related to the control experiment. However, due to the degradability of the fibres, treatment may be required to improve the fibre properties.

This study explored the novel use of pine needle and sisal fibre composites in concrete, offering a sustainable alternative to traditional construction materials. The synergistic combination of pine needles, and sisal fibres makes this research unique and different from most research studies. The innovative approach also addresses waste management concerns, reduce reliance on synthetic materials, and contributes to the development of environmentally friendly building solutions. This research has synthesized existing knowledge on strength properties of concrete incorporating pine needle and sisal fibre composites, sustainability challenges faced in NFRC use, benefits of NF materials, revealing key insights and notable gaps in the literature. By bridging some of these gaps, this study enhances our understanding of strength properties of concrete incorporating pine needle and sisal fibre composites and puts forth the base foundation for the future investigations and provides actionable recommendations ultimately contributing to the development of sustainable building materials.

The novelty of this research lies on the innovative combination of two locally-sourced natural fibres with unique properties to create a hybrid-fibre reinforced concrete. With the intent of understanding the synergistic effect of the hybrid materials, improving the strength properties of concrete while promoting sustainable construction practices and mitigating climatic and environmental problems.

3. CHAPTER THREE: MATERIALS AND METHODS

3.1. Introduction

This section explains the steps, methods, materials that were used to achieve the objectives of this research. It also elaborates how materials were selected, sorted and how the specimens were prepared for experimental testing including data analysis, comparative analysis and reporting. The study methodology was deliberately designed to investigate the intricacies of concrete specimen behaviour, employing a robust and structured framework that integrates experimental and analytical techniques. By outlining the research design, experimental program, testing methods, and standard procedures, validation methods, this section provides a clear roadmap for understanding the study's approach employed to achieve its goals.

3.2. Research design

The research-study considers a comprehensive quantitative experimental design for research to investigate strength properties of concrete incorporating pine needle and sisal fibre composite. The design enables variable manipulation to observe effects on strength properties, providing valuable insights into material behaviour. By adopting an experimental approach, and stimulation method, this research establishes cause-and-effect relationships between variables and digs out correlation understanding. Experimental testing techniques, including tensile, flexural and longevity tests (fibre degradation) is used to collect data. Statistical analysis including regression modelling and correlation analysis is performed using Sigma Plot software and the analysis of variance (ANOVA) to examine relationships between variables and identify significant trends.

The experimental methodology is chosen for its ability to establish cause-and-effect relationships, provide precise measurements, and control extraneous factors. This design allows for comprehensive investigation of research questions, enabling development of robust understanding of material properties, relationships and correlations ([Abdallah, 2025](#)). To ensure external validity, results and regression models are compared with related existing research data and models. Internal validity is ensured through adherence to proper selection, sorting, treatment of materials, standard measuring, testing procedures and quality control checks ([Fiona, 2025](#)). Reliability is ensured through consistency in experimental setups and conditions, tool usage, and procedural adherence.

The study acknowledges limitations, including time constraints, financial limitations, and equipment inadequacies. Effective time management methods, proper planning, and resource allocation, including borrowing of funds from friends are employed to mitigate these limitations. This study adds to the existing informative-knowledge by putting forth new ideas and insights into strength characteristics of NFR hybrid and concrete composites-materials incorporating pine needles and sisal fibres. Findings have implications for sustainable building material development, informing, policy and decision making in the engineering industry. By employing the experimental methods, the study managed to gather accurate and reliable data, analyse and draw meaningful conclusions and recommendations.

3.3. Experimental program

A comprehensive experimental program was undertaken to elucidate the properties and behaviour of Natural Fibre-Reinforced Concrete (NFRC) incorporating pine needle and

sisal fibres. The primary key objective of this study research endeavour was to systematically understand the implication of varying proportions of pine needles and sisal fibres on the strength attributes of concrete (NFRC), determining the optimal fibre contents therefore enhancing the strength properties of concrete for sustainable applications. The criteria in this research were based on the concrete strength properties, in this case the fibre proportion that yielded the best workability and highest concrete strength properties, say, split tensile, flexural and, compressive strength was considered the balanced fibre content.

The fibre contents considered in the experiments were selected based on review of the literatures for related studies that yielded better strength. And to answer the key specific objective 2 of the research-study i.e. to examine the effect of fibre contents on the strength properties of concrete while establishing the optimal fibre proportions and maintaining the workability and flowability, this in line with most current research for example ([Yusra et al., 2024](#)) and many other studies. Also, considering the fibre physical and mechanical properties, these ratios were appropriate for research. The detailed experimental program utilised in the present study is shown in [Table 3.1](#).

Table 3.1 Experimental program

Material composition and sample types	% of fibres by weight in concrete	Laboratory Tests
Plain Concrete (control experiment)	0	Physical and mechanical property tests for fibres, Material tests (sand and aggregates), workability test. Compressive, Split tensile, Flexural strength tests, Durability (Fibre degradation), and water absorption test.
Sisal fibres proportions	0.1	
	0.2	
	0.5	
	1.5	
	0.1	
Pine needle fibres proportions	0.2	
	0.5	
	1.5	
	0.1:0.1	
Composite, Sisal fibre: Pine needle fibre ratio respectively	0.2:0.2	
	0.5:1	
	01:0.5	
Split tensile test samples	48	
Samples for Compressive strength test	124	
Samples for the control experiment	72	
Samples for absorption test	9	
Samples (beams) flexural strength test	4	
Durability test, beams reinforced with steel, with varied concrete covers	12	
Total number of samples	269	

3.4. Materials

3.4.1 Material sampling and preparation

All materials were acquired in February 2025. Pine needle fibres were collected from mature pine trees (age > 20 years) at Kyambogo University plantation. To ensure quality assurance, the dry pine needles were collected from healthy tree, cleaned to remove

impurities. Physical and mechanical tests were conducted on the pine needles in the laboratory.

Sisal fibres were sourced from Mukono district in the central region of Uganda and processed to extract the fibre. Quality assurance measures included cleaning, sorting and testing the fibres for mechanical and physical characteristics in the laboratory. The aggregate used in this study were machine crushed stone aggregate originating from Mukono district but sold in Kireka, Kampala (see [Figure 1.1b](#)), with a maximum diameter of 20mm. the aggregates were tested for sieve analysis, impact resistance, crushing value, specific-gravity, water absorption and flakiness index. Sand used in this study was natural lake sand purchased from Kireka, Kampala. The fine aggregate was taken for sieve analysis, specific gravity, water absorption, finesse modulus and moisture content.

Material characterisation techniques used in this study include sieve analysis to determine particle size distribution, impact resistance test to determine toughness, flakiness index test to determine flakiness. Crushing value test to determine strength, water absorption and specific-gravity tests to determine density and water absorption capacity. Sample preparation involved pretreatment, including cleaning sorting, and sizing of materials to meet requirements specifications. The samples were then moulded to required shapes and sizes. Post treatment involved curing the samples under controlled conditions to achieve the desired properties, and documentation of all samples was done in each process, records were taken including for material properties, sample marking for dates and identification during moulding and tests specified.

3.4.2 Pine needle fibre preparation

A rigorous preparation protocol was implemented to guarantee uniformity and consistency of pine needle fibres. Mature fibres were meticulously selected and subjected to a comprehensive sorting procedure to eliminate impurities, debris, and damaged fibres, ensuring only superior fibres were utilized. The fibres then underwent a thorough cleaning process to remove residual impurities and contaminants. To achieve uniform fibre diameters, the tapered ends were excised, and only fibres with consistent diameters were retained. This step minimized variability in fibre properties and behaviour within the concrete composite.

The cleaned and sorted fibres were then precisely cut into 2 cm lengths, a dimension chosen based on an exhaustive review of existing literature and preliminary studies that indicated optimal mechanical properties for this length. The pine needle fibre sorting and sizing processes are shown in the [Figure 3.1](#).



[Figure 3.1](#) Pine needle fibre preparation

The cutting process was done carefully to ensure uniform fibre lengths, through marking of the fibres facilitating optimal dispersion and distribution within the concrete matrix. The prepared pine needle fibres were then ready for integration into the concrete mixture, enabling the creation of a uniform and consistent composite material. The me-

ticulous preparation of fibres was crucial in ensuring the resulting composite material exhibited enhanced mechanical properties, including strength, toughness, and durability.

3.4.3 Sisal fibre preparation

A systematic extraction and preparation method and protocol was followed to guarantee uniformity and consistency of sisal fibres. Sisal leaves were harvested and subjected to a mechanical decortication process to extract fibres, followed by a thorough cleaning procedure to remove impurities and debris. The fibres underwent a stringent sorting process to eliminate damaged or inferior fibres, ensuring only premium fibres were utilized. To achieve uniform fibre diameters, the fibres were manually refined to remove excess pulp and impurities. The cleaned and sorted fibres were then precisely cut into 2 cm lengths following the uniform marks of 20mm formally marked on fibres (see [Figure 2.3](#)), a dimension selected based on an exhaustive review of existing literature.

Figure 3.2 The process of weighing sisal fibres prior to its final preparation for incorporation into concrete



The cutting process was carefully controlled to ensure uniform fibre lengths, facilitating optimal dispersion and distribution within the concrete matrix. The prepared sisal fibres were then ready for integration into the concrete mixture, enabling the creation of a uniform and consistent composite material. The meticulous preparation of fi-

bres was crucial in ensuring the resulting composite material exhibited enhanced mechanical properties, including strength, toughness, and durability.

3.4.4 Cement

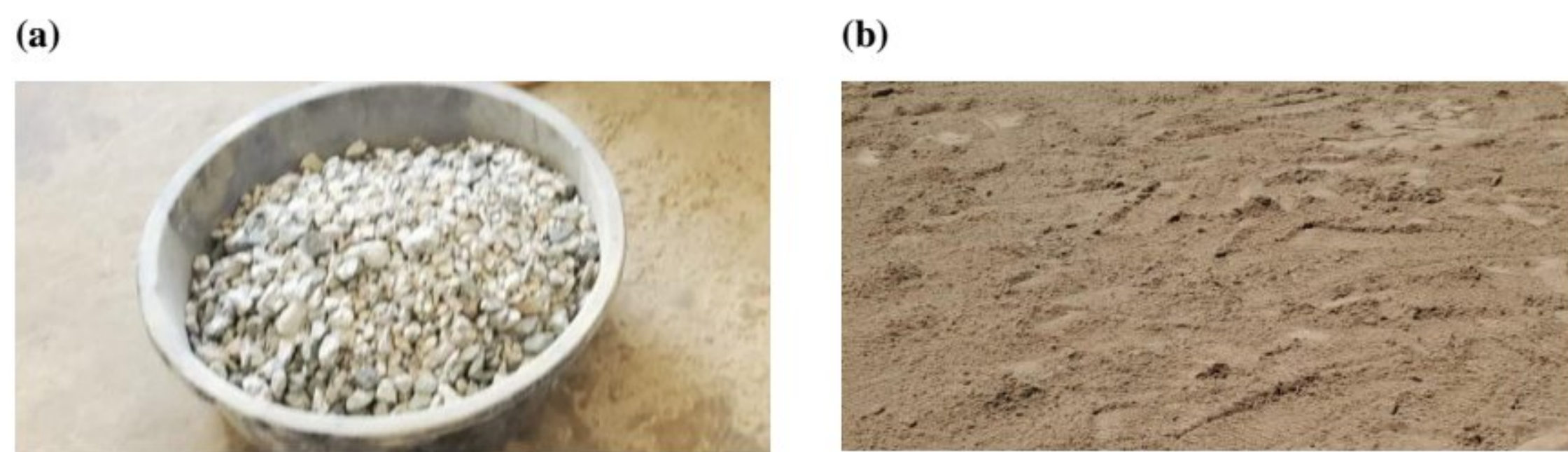
The cement utilized in this investigation is Cem II 32.5N, manufactured by Tororo Cement Limited. This cement type is a composite blend of clinker and supplementary materials like limestone, fly ash, or slag, carefully proportioned to achieve optimal performance. It adheres to pertinent standards for cement quality and performance, including EN 197-1:2011 and Uganda National Bureau of Standards (UNBS), specifying requirements for cement composition, properties, and conformity criteria. The cement has a compressive strength of 32.5MPa, an initial setting time ≥ 60 minutes, and a final setting time ≤ 10 hours, with soundness of ≤ 10 mm. All materials were acquired in February 2025. The choice of OPC and class 20N/mm² of concrete was informed by their widespread availability, affordability and suitability for general construction. The class 20N/mm² meets the moderate requirements for the research, cost effectiveness, and above all, the concrete class has no effect on the on the research findings, any design strength could be used.

3.4.5 Coarse and fine aggregates

The coarse aggregate (see [Figure 3.3a](#)) employed in this research was machine-crushed, featuring a maximum aggregate size of 20 mm. Sourced from a local quarry, the aggregate underwent rigorous selection and testing process to ensure compliance with requisite standards. The mechanical crushing process yielded aggregate particles with a rugged texture and angular morphology, enhancing the mechanical interlock between the aggregate and cement paste. The physical attributes of the aggregate include Specific

gravity of 2.6-2.8, indicating a dense and robust material, Absorption of 0.5%, signifying moderate water absorption capacity

The lake sand (see [Figure 3.3b](#)) used in this research was gotten from the local lake deposits, undergoing meticulous evaluation to ensure adherence to stringent concrete production standards. Its natural provenance and geological history endowed the sand with distinctive features, including a smooth surface texture and rounded particle shape. The lake sand's physical properties comprise; Specific gravity: 2.6, denoting a relatively high density, Absorption: 0.5%, indicating a moderate capacity for water absorption, fineness modulus of 2.65%, silt content of 2%, and soundness of 1.3% Gradation: well-graded (see [Figure 4.2](#)) facilitating optimal particle packing and concrete performance. The utilization of this lake sand significantly enhanced the flowability, strength, and longevity of the concrete mixture, rendering it an ideal component for various construction applications. The sand's unique characteristics and properties played a key responsibility in ensuring the consistency and reliability of the concrete's performance.



[Figure 3.3](#) Coarse and fine aggregates used in the study

3.5. Experimental design

3.5.1 Sample design

1. Mix design, C-20, class concrete.
2. Fibre reinforcement in concrete.
 - a) Plain concrete, zero fibre volume or weight,
 - b) Pine needles (0.1, 0.2, 0.5%, and 1.5% by weight),
 - c) Sisal fibres (0.1, 0.2, 0.5%, and 1.5% by weight), and 2% for specific samples.
 - d) Composite (pine needle and sisal fibre respectively, 0.1%+0.1%, 0.2%+0.2%, 0.5%+0.5%, 0.5%+1%, 1%+0.5%, by weight).

3.5.2 Specimen preparation

1. 150mm × 150mm × 150mm cubes (compressive strength).
2. Cylinders 200mm × 100mm (Split Tensile strength test).
3. Beams for flexural strength tests of 750mm × 150mm × 150mm, (bending/flexural Strength) were cured under controlled conditions for 28 days to achieve full strength.
4. Cubes of 150mm × 150mm × 150mm reinforced with round 12mm steel bars with varied concrete covers.

3.5.3 Mixing and Sample preparation Process

This study employed a meticulous mixing and sample preparation protocol to ensure the production of high-quality concrete samples. The protocol consisted of the following:

1. **Material preparation and batching:** Precise measurement and preparation of materials, including cement, coarse aggregate, lake sand, and sisal fibres, were conducted according to designated mix proportions.
2. **Dry mixing process:** A pan mixer was utilized for dry mixing of cement, coarse aggregate, and lake sand for 2-3 minutes, ensuring uniform material distribution.
3. **Fiber dispersion:** Sisal fibres were put to the dry mixed materials and mixed for an additional 2-3 minutes, guaranteeing uniform fibre dispersion.
4. **Wet mixing and hydration:** Water was added, and the mixture was wet mixed for 3-5 minutes, achieving a consistent and workable mix. The mixing process was complete when the mixture exhibited a uniform consistency and texture.

3.5.4 Experimental set up

The experimental program employed in this study consists of material collection, preparation, batching, mixing, workability tests, sample casting and curing, and performance evaluation. This setup is detailed in [Figure 3.4](#).



[Figure 3.4](#) Experimental set-up.

3.5.5 Sample preparation and mechanical testing

The mixed concrete/composite was used to prepare samples for various mechanical tests(moulding), including compressive strength test, split tensile test, flexural strength test, shrinkage and cracking test. For each test, a control experiment was conducted us-

ing plain concrete (without fibres) as a control experiment. Fiber-RC samples were prepared with sisal fibre proportions of 0.1%, 0.2%, 0.5%, and 1.5%, weight. Samples were cast into moulds, as seen in [Figure 3.5](#), specifically designed for each test and cured in a controlled environment following standard laboratory procedures. Tests were conducted on different days, with each test having its own control experiment. The testing schedule was carefully planned to ensure all samples were tested at designated ages. Quality control measures were implemented throughout the mixing and sample preparation process.

[Figure 3.5](#) Casting of concrete samples



3.6. Laboratory testing

3.6.1 Pine needle fibre tests

The physical and mechanical attributes of pine needle and sisal fibres were assessed through a series of experiments, including fibre diameter assessment and microscopy were employed to measure the diameter of individual fibres, ensuring precise characterization. Tensile property evaluation, a universal testing equipment was used to determine the breaking elongation and force at break of the fibres, providing insights into their tensile behaviour. The tensile strength of the fibres was calculated based on the

measured breaking force and diameter, allowing for a critical understanding of their mechanical nature.

The elastic modulus of the fibres was derived from the stress-strain curves obtained during tensile testing, providing valuable information on their stiffness. These experiments were conducted in strict adherence to British Standards BS EN ISO 5079, to guarantee the accuracy and reliability of the results. By employing this rigorous testing protocol, the study aimed to unleash a thorough knowledge of the mechanical and physical characteristics of pine needle and sisal fibres, ultimately informing their potential application as reinforcement materials in concrete. The equipment used in testing the mechanical and physical characteristics of the fibres include: Universal Testing Machine for tensile strength, scanning electroscope for the diameter of fibres, water absorption apparatus, YG003E single fibre strength tester.

3.6.2 Concrete compressive strength test

This investigation utilized the compressive strength test machine (see [Figure 3.6](#)) to assess the ability of concrete specimens to resist compressive forces, following BS EN 12390-3:2019. Standardized cube specimens were prepared using a consistent mixing and compaction procedure to ensure uniformity. The specimens were cured in by dipping the specimens in water for 7, 14, and 28 days to know the growth or increase of compressive strength over time. And then the sample-specimens were then subjected to compressive loading, and the highest force at fracture was recorded. Compressive strength was calculated from the maximum load at failure, providing knowledge on the material's capacity to resistance compressive stress. Various fibre proportions (0.1%, 0.2%, 0.5%, and 1.5%) of pine needle and sisal fibres were incorporated into the con-

crete mixture to examine their impact on compressive strength. This investigation utilized the compressive strength test to assess the capacity of concrete specimens to resist compressive forces.

Figure 3.6 Sample Testing for compressive strength



3.6.3 Split tensile strength test

The split tensile strength test, was undertaken according to BS EN 12390-6:2009, evaluated the tensile strength of concrete specimens. Standardized 100mm x 200mm cylinder specimens were prepared using a consistent mixing and compaction procedure and cured for 7, 14, and at the 28th day. The sample-specimens were again tested under tensional loading by use of a testing equipment, applying the load along the diameter of the specimen. Split tensile strength was computed by use of the formula:

$$\sigma = 2P/\pi DL \quad \text{Eq. (3.1)}$$

where σ is considered to be the split tensile strength, and P is said to be the maximum load, D is the diameter of the specimen, and L is the length of the specimen. This test provided valuable information on the material's tensile properties.

3.6.4 Flexural strength test

The flexural strength test, adhering to BS EN 12390-5:2019, evaluated the ability of concrete specimens to withstand flexural loads. Standardized 150mm x 150mm x

750mm beam specimens were prepared using a consistent mixing and compaction procedure and cured for 28 days. Specimens were tested under flexural loading using a testing machine, applying the load at the midpoint of the specimen. Flexural strength was calculated using the formula:

$$\sigma = 3PL/2bd^2 \quad \text{Eq. (3.2)}$$

where σ is the flexural strength, and P is the maximum load, L is the span length, b is the width of the specimen, and d is the depth of the specimen. This test provided insight into the material's flexural properties.

3.6.5 Pine needle and sisal fibre RC degradation test and impact on the steel rebar

The objective of this test was to investigate the resistance of the pine needle and sisal RC on the alkaline environments and also as a result to come up with the suitable cover thickness which could protect the concrete embedded reinforcement steel possibly protecting the steel from corrosion. With the key focus on determining the optimal concrete cover thickness for minimising corrosion of steel which could be caused due to fibre degradation and failure to of the fibre concrete material to and failure to protect the steel rebars, for recommendations in large natural fibre-reinforced concrete applications based on durability test principles.

A total of 12 samples with 12mm round-steel reinforcement bars in the concrete cube specimens (150mm × 150mm × 150mm) were cast, the specimens were made with four different concrete mixes which includes plain concrete (0% fibre content), concrete with 0.1% pine needle fibres, concrete with 0.1% sisal fibre content, concrete with

1.0%: 0.1% ratio of pine needle to sisal fibres respectively by weight, all with varying concrete covers starting from 15mm, 20mm, and 30mm.

Round-steel reinforced concrete specimens were cast with single reinforcement bar embedded in each 150mm cube concrete specimen. The concrete cover thicknesses were varied by adjusting the length of the steel bars and their positions in each specimen to achieve required concrete cover. The initial appearance and surface of all the cubes were observed before and after the test experiment. The specimens were immersed in a 2.5 M 10% concentrated sodium hydroxide solution (NaOH) alkaline solution for 60 days to simulate an alkaline environment and accelerate the fibre degradation in high PH environment which could possibly expose the rebar into a corrosive environment. After 60 days, the specimens were removed from NaOH solution and the final observation made, the results are elaborated in chapter four.



Figure 3.7 Pine needle and sisal fibre RC degradation (Durability test)

3.7 Economic viability and environmental benefit analysis

The economic viability and environmental benefits of pine needle and sisal fibre-reinforced concrete were evaluated through a meticulous analysis. A detailed cost-benefit analysis was executed to understand the economic feasibility of utilizing pine

needle and sisal fibres in concrete production, taking into account the costs of fibres, reinforcement materials, and production processes. Furthermore, a carbon dioxide gas analysis was performed to quantify the environmental impacts of pine needle and sisal fibre-reinforced concrete, encompassing greenhouse gas emissions, energy consumption, and waste generation. The results were then compared to those of traditional concrete to determine the potential environmental advantages of incorporating pine needle and sisal fibres.

To determine the cost per unit of work in the production process of pine needle and sisal fibre reinforced concrete, the following information was required labour output per day for various tasks considering the material production process, also known as productivity; accurate rates for various equipment, tools used in sorting and processing of fibres and materials used in the production of the composite; accurate market prices of materials at the time of use as prime costs; and correct wage rates for various categories of skilled and unskilled labourers for daily work, including sorting of fibres, sizing, cleaning, and mixing.

Rate analysis involves fixing the cost per unit of measurement for different items of work considering a typical beam element of $0.3\text{m} \times 0.4\text{m} \times 3\text{m}$, volume of 0.36m^3 of concrete. The total cost per unit of work (TC) consists of two components: direct cost (DC) and indirect cost (IC). Direct costs include material costs, labour costs, and equipment and tools costs. Indirect costs, on the other hand, cover overhead costs, which facilitate workers and labourers sorting materials, as well as miscellaneous items. These overhead costs were essential for the workers but were not directly considered in the best cost benefit analysis. By analysing the data collected from the cost-benefit

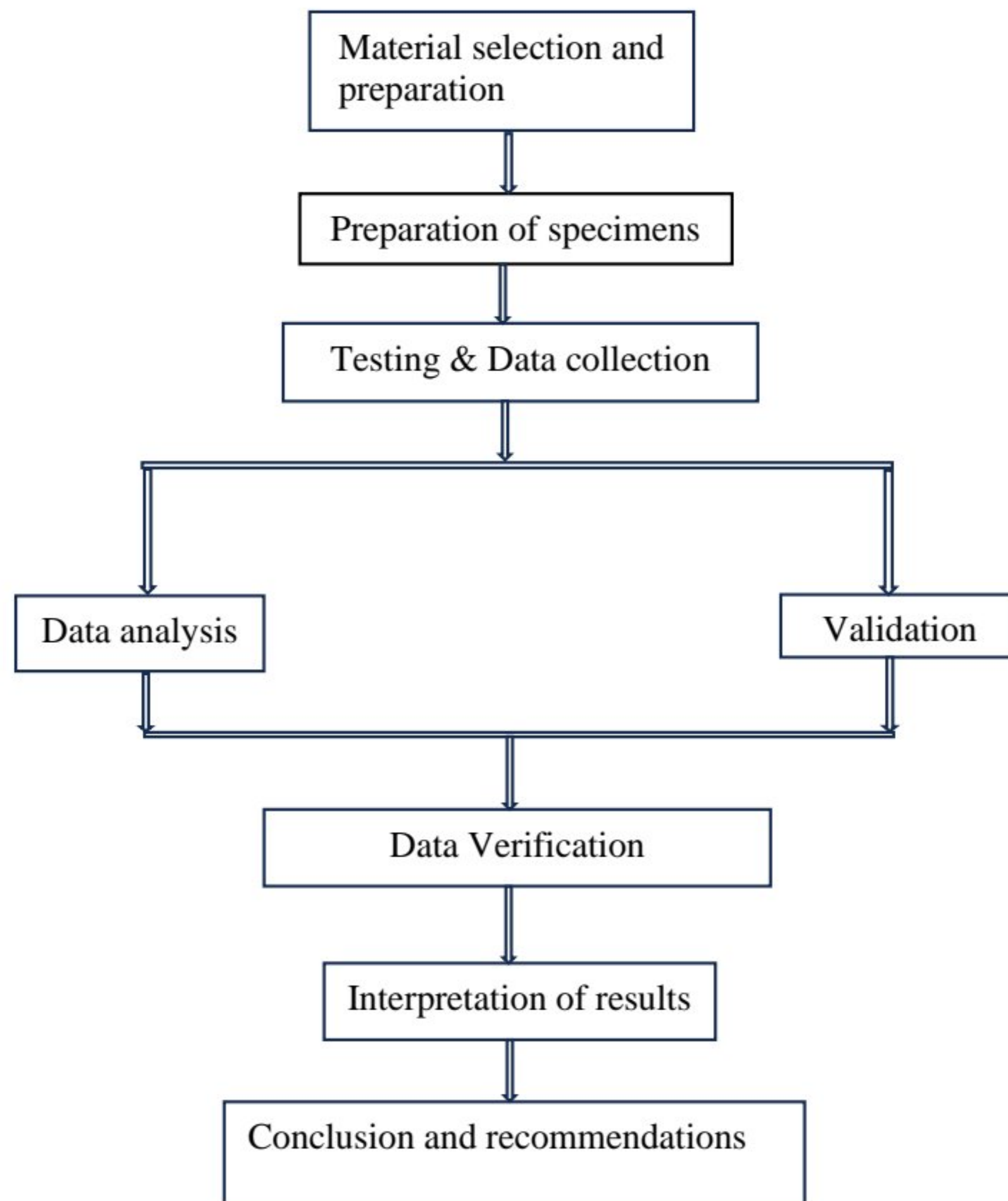
analysis, this study aimed to unleash key-important information into the economic and environmental sustainability of pine needle and sisal fibre-reinforced concrete.

3.8. Data analysis and collection instruments

Data was organised, prepared, synthesized, plotted, using sigma plot software, and analysed using a regression model. Statistical analysis: through descriptive statistics, generation of mean standard deviation, R-square and P-values, residual values, standard error generated and coefficient of variation and correlation between variables generated for compressive, tensile and flexural strength. Compare mean strength values among different fibre proportions and volume fractions and model relationships between fibres and concrete strength properties. The statistical method used in this study was regression model analysis to model the relationships between fibre content and concrete properties. sigma plot software and analysis of variance (ANOVA) were used for data analysis and including the graphical-representation. Descriptive statistics, mean standard deviation, P-values, F-values, mean square values were read directly from the regression model report with prediction linear equations developed. Regression analysis performed using Sigma Plot software and ANOVA to model the relationship between the variables and descriptive statistics, mean, standard deviation, also to test the statistical significance in the perceived differences in the data result.

Data visualization: plot stress strain curves, generate bar charts and line graphs for concrete composite strength properties. Results were interpretation evaluated for the impact of fibre-proportions, volume fractions onto the composites strength properties, to identify the optimal fibre configuration, discuss implications for concrete design. Concrete mixer, Casting Molds, Curing Chamber, Gauge boxes, Universal Testing Machine

(compressive and tensile strength), Data collection sheets (concrete mix design forms, specimen preparation check list, testing protocol form, data recording sheet. The detailed methodological flow cart is shown in [Figure 3.8](#).



[Figure 3.8](#) Methodology flow chart

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Introduction

The chapter herein gives a thorough presentation and elaboration of the experimental results obtained from investigating the strength properties of the concrete hybrids improved with pine needle and fibres extracted from sisal. As stated in [Section 1.3.1](#), the primary goal of this research was to assess the strength characteristics of the concrete incorporating pine needle and sisal fibre composites, focusing on key characteristics like flexural, split tensile, linear shrinkage, compressive strength and cracking. A range of tests (refer to [Section 3.6.3](#)) were conducted on various concrete mixes, sand, aggregates and natural fibres, to dig for a deeper information about the composite's behaviour.

Herein the findings of the test-experiments are presented and explained in depth, rendering valuable key-informative points into the effects of fibre reinforcement on the strength and durability of concrete. Whereas Sigma plot software ([Section 3.2.1](#)) was utilized to analyse and interpret the data, identifying trends, correlations, and significant differences between the various concrete mixes. The statistical examination was done to ascertain the significance of the data collected and to identify the most influential factors affecting the properties of concrete.

This Chapter is structured into several sections each focusing on aspects of the results obtained as per the specific objectives. To begin with, material test results including mechanical, physical characteristics of materials like natural fibres used, aggregates and sand are presented and discussed prior to a detailed analysis of the concrete

strength properties (e.g., split tensile, flexural, and compressive strength, water absorption) and corrosion tests results along with a discussion into the findings.

4.2 Material tests and their properties

The intrinsic properties of aggregate, sand and natural fibres used in this study were thoroughly characterised through a series of material tests, including sieve analysis, absorption test, flakiness index test, soundness test, to determine important material parameters like flakiness index, finesse modulus, silt content, abrasion value, Aggregate crushing value, and so forth. These material characterisation helps in understanding material properties hence ensuring quality, suitability, mix design optimisation, prediction of material performance, and validation of research hypothesis hence reliable, valid and applicable findings in the real world.

4.2.1 Mechanical and physical characteristics of coarse aggregates

The coarse aggregates are fundamental components of concrete, occupying a significant volume fraction and playing a crucial role in determining the mechanical properties and durability of the final product. The mechanical and physical characteristics of coarse aggregates for example gradation, crushing value, abrasion value, and flakiness index, water absorption, and also, impact value, are herein shown (see [Table 4.1](#) and [Figure 4.2](#)).

Table 4.1 Physical and Mechanical properties of coarse aggregates

Material property	Value	Recommended British standard
Specific gravity	2.6	(2.5-3) %
Flakiness index	27%	$\leq 40\%$
Soundness test	1.30%	$\leq 12\%$
Loss angles abrasion value	28%	(30-50) %
Aggregate crushing value	15%	$\leq 30\%$
Water absorption	0.5-0%	(3-4) %

Gradation, see [Figure 4.1](#), with a nominal size range of 5-37.5 mm, fakeness index of 27%, soundness of 1.3%, abrasion value of 28%, dry crushing value (DCV) of 15%, mean dry impact value of 9% ensuring optimal packing density and concrete performance. The incorporation of this coarse aggregate contributed significantly to strength, stability, and longevity of the concrete mixture, rendering it well suited for diverse building and construction applications. The careful selection and characterization of the aggregate ensured consistency and reliability in the concrete's performance.

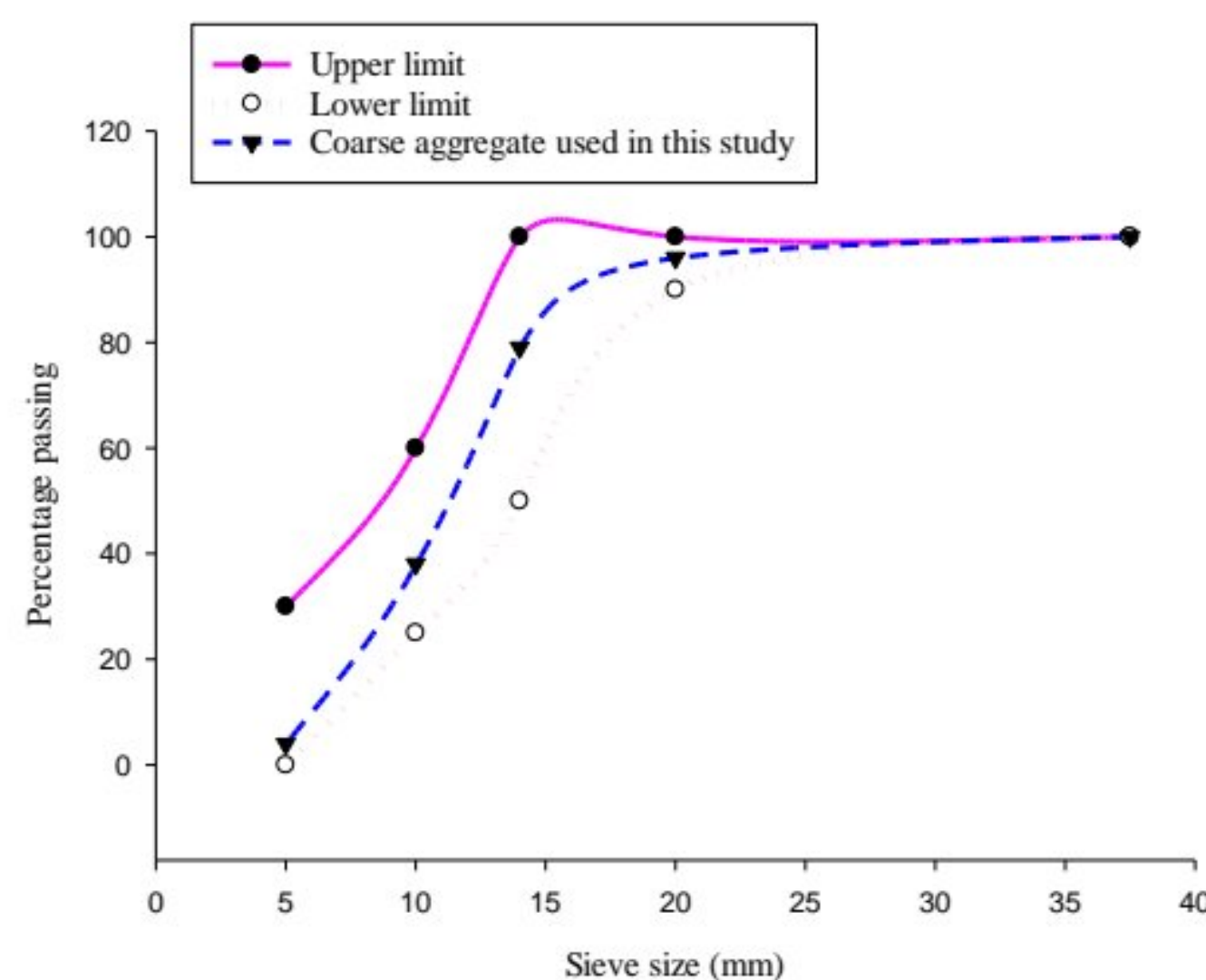


Figure 4.1 Gradation curve for coarse aggregates, super-imposed on the BS882: 1992 specification for aggregates from natural sources for concrete.

The aggregate test results conform to the British Standards, demonstrating suitability for use in the concrete production and applications. The aggregate exhibit suitable density, good particle shape and high resistance to weathering. The aggregate also shows good resistance to abrasion and high strength. The lower water absorption suggests durability and resistance to degradation, collectively indicating that the aggregate meets the standard suitable for its use. From the gradation curve shown in [Figure 4.1](#), the coarse aggregate material which were used in this particular research was well graded, it lies within the limits.

4.2.2 Mechanical and physical characteristics of fine aggregates

The sand characterisation involved a comprehensive evaluation of its physical properties, including gradation, determination of silt content, and finesse modulus. As fine aggregate with the fineness modulus characteristic equivalent to 2.65, silt content of 2%, sand helps to fill the air spaces in the concrete and enhances the overall performance of concrete. The evaluation in sand characterization aimed at determining the sands compatibility and potential efficacy in the improvement of the concrete composite's mechanical properties as shown in [Figure 4.2](#). The sand gradation curve exhibits gradual increase in percentage passing, ranging from 0.2% to 100%, indicating a relative uniform particle size distribution with a fineness modulus of 2.6.

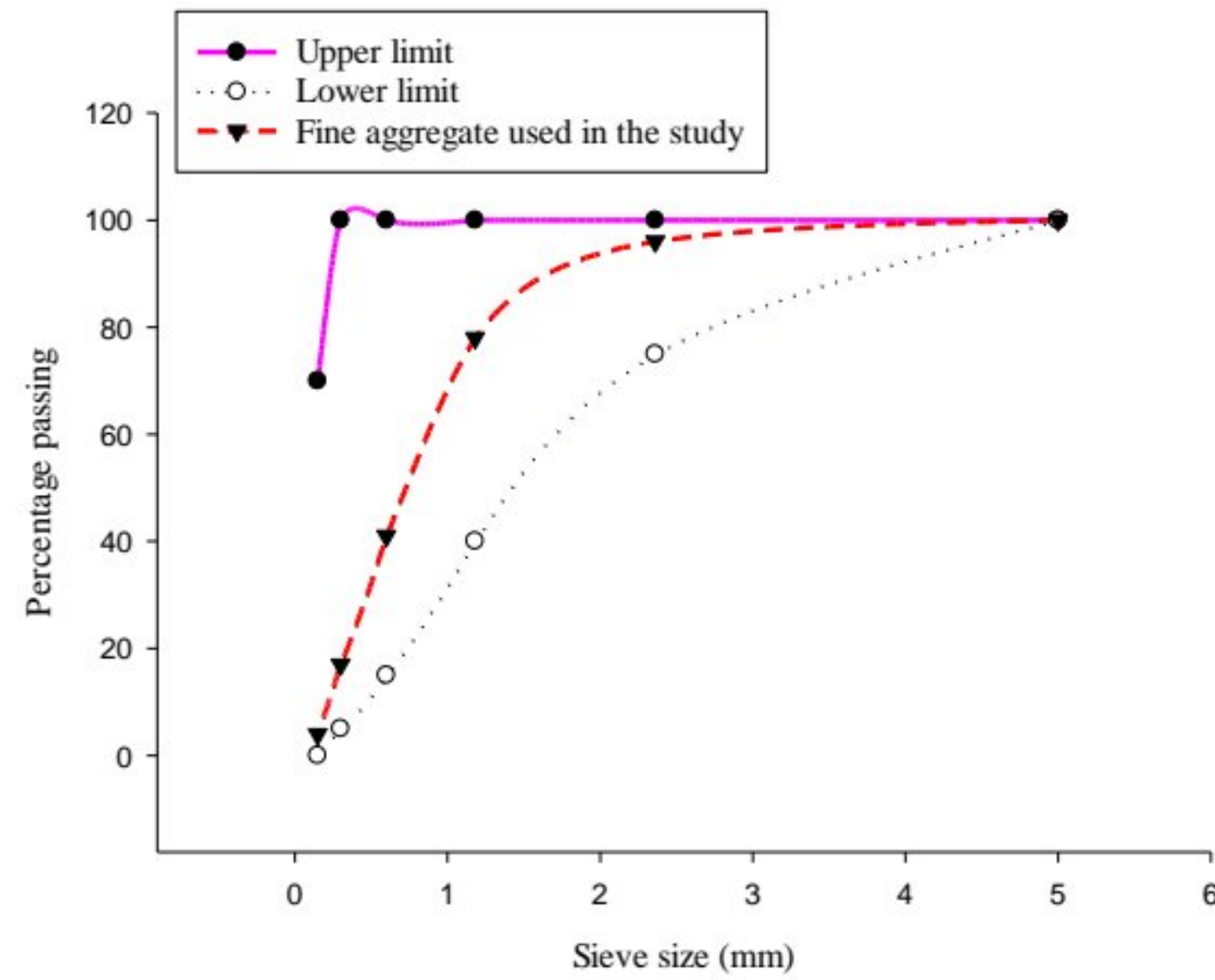


Figure 4.2 Gradation curve of fine aggregates, super-imposed on BS882:1992 specification for aggregates from natural sources for concrete

This uniformity suggests that the sand can provide a good balance between flowability and stability in concrete mixtures. The fineness modulus of 2.6 falls within the range for various concrete applications, implying that the sand can contribute to good workability and strength, and the medium sand classification and moderate fineness modulus suggests that the sand is suitable for use in concrete production and its gradation characteristics can help to achieve optimal concrete performance. From the gradation curve, (see [Figure 4.2.](#)), the fine aggregate used was well graded.

4.2.3 Mechanical and physical characteristics of pine needle and sisal fibres

Natural fibres like pine needle and sisal fibres possess distinct physical and mechanical attributes depending on their nature, origin and species, these attributes tender them for versatile applications. By examining these properties, this study seeks to elucidate the inherent characteristics of this fibres and their potential utility in composite materials.

The test results shown in [Table 4.2](#) revealed distinct physical attributes and mechanical characteristics of pine needle and sisal fibres with sisal fibres exhibiting superior breaking force, tensile strength, and elastic modulus, making them a primary contributor to strength and stiffness in the concrete composite material ([Geremew et al., 2025](#)).

Table 4.2 Physical and mechanical characteristics of pine Needle and Sisal fibres

Fibre parameter	Pine	Sisal	Some characteristics according to ASTM D3822
Diameter(micrometre)	0.51	0.23	0.1 – 0.5
Breaking force (N)	318.68	512.4	–
Breaking elongation %	2.18	5.43	1 – 10
Tensile strength (MPa)	15.6	123.34	$\geq 200 - 500$
Elastic modulus (GPa)	0.716	2.27	2 – 30

However, pine needle fibres play a critical role in enhancing toughness and ductility due to their relatively lower elastic modulus and moderate breaking elongation. The (0.45 - 0.58) micrometre diameter of pine needle fibres contributes in improved crack bridging as larger fibres are good in bridging cracks and resistance to crack propagation ([Pham, 2025](#)). It is observed that 0.45 – 0.58 micrometre fibre diameters help in energy absorption contributing to improved toughness and impact resistance, enhanced load transfer since larger fibres can transfer loads more efficiently, potentially improving on materials strength and stiffness ([Mazur, et al., 2022](#)).

4.2.4 Natural fibre reinforced concrete slump tests

The tests of the slump are a widely used method to examine the flowability the consistency of the freshly formulated concrete, playing a crucial role in aligning the class and longevity of concrete structures. By testing the slump values, we can determine the concrete's ability to flow and fill moulds of formwork, which directly impacts its

placement, compaction and finishing. This test is essential in evaluating the impact of NF addition on concrete's rheological characteristics. In this section, I present the results of slump tests conducted on concrete mixes reinforced with pine needle and sisal fibres, in relation to the control experiment, to understand the effect of these fibres on workability and potential implications for concretes strength and durability.

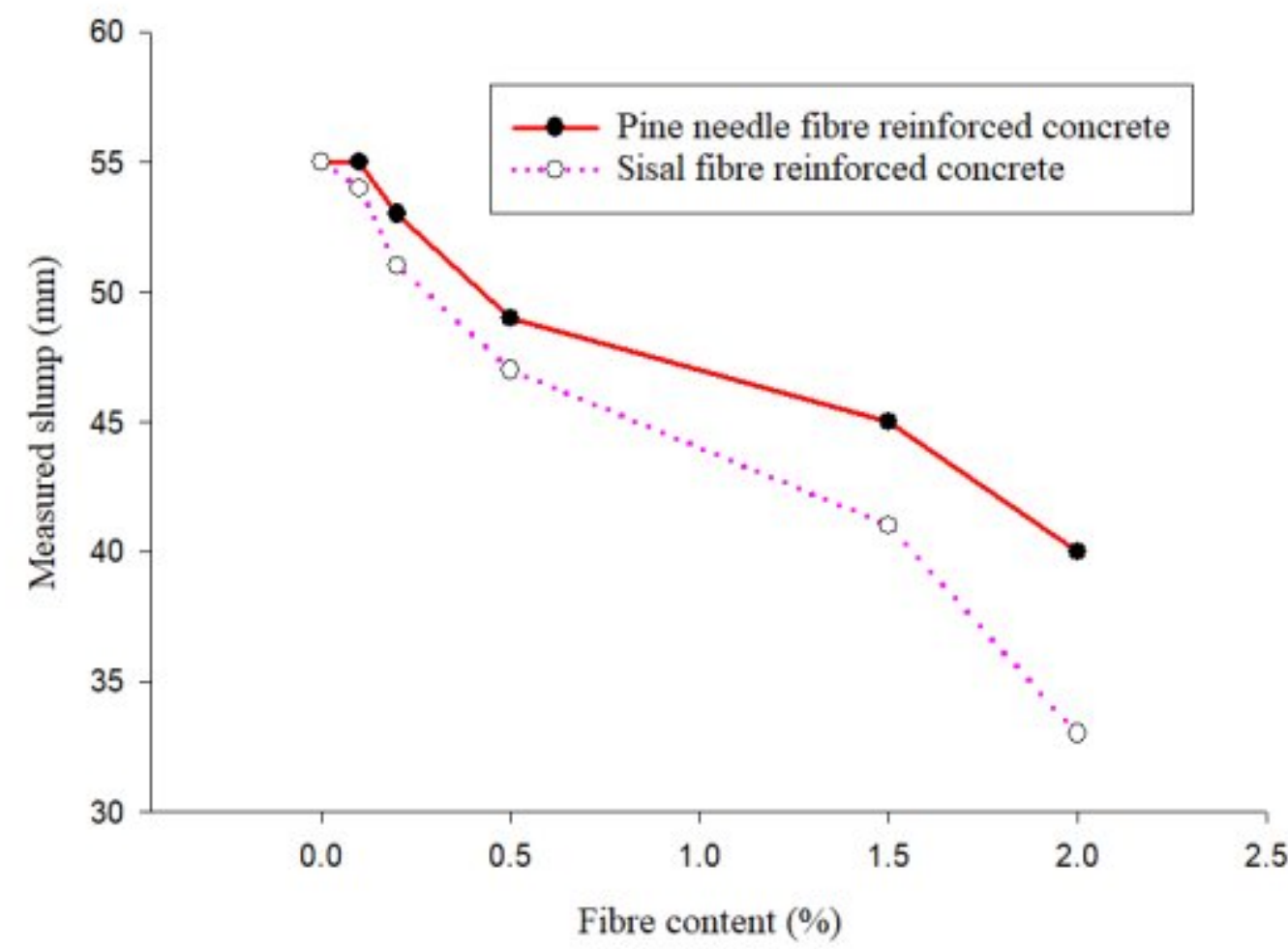


Figure 4.3 Concrete slump test

The test of the slump results indicates that as fibre content increase, workability decreases. Both pine needle and sisal fibre reinforced concrete exhibit this trend, likely due to increased internal friction and reduced flow ability caused by the fibre friction. Sisal fibres reinforced concrete shows a more significant reduction in slump compared to pine needle reinforced concrete, suggesting differences in fibre properties influence fibre cement-paste interaction and workability.

4.3 Concrete strength properties

4.3.1 Compressive strength of pine needle fibre-reinforced concrete

This experimental investigation aimed at evaluating the characteristic strength of concrete incorporating fibre composites, with a design target of 20Nmm^2 characteristic concrete strength. As recorded in [Figure 4.4](#), the effect of varying pine needle fibre content (0%, 0.1%, 0.2%, 0.5% and 1.5% by weight) on compressive strength of concrete were explored at different testing ages (7, 14, 21 and 28 days).

The neat specimen, (control experiment) portrayed the highest compressive strength values across the testing ages with an average 28th-day strength of 33.32N/mm^2 exceeding the design target. The use of pine needle fibres led into a drop in compressive characteristic strength of NFRC compared to the control specimen, the high content fibres causes inhomogeneous mix, low workability affecting the interface attraction force with the concrete matrix, it could also be because of formation of balling, increased porosity in the composite ([Shrestha et al., 2024](#)).

A same behaviour has been registered in such studies. However, the 0.1% and 0.2% fibre reinforced concrete samples showed promising results with average 28th-day strength of 23.06N/mm^2 and 22.21N/mm^2 , respectively. These values are still above the minimum requirement for class 20 N/mm^2 concrete, indicating potential applicability of these fibre contents in structural concrete as shown in [Figure 4.4](#) and [Figure 4.5](#). The single sisal fibre reinforced concrete of ratio 0.1% fibre performed more with the compressive characteristic strength of 27.5N/mm^2 compared to the composite concrete ma-

terial with 0.2% each combined fibres, which yielded a compressive strength of 23.7N/mm².

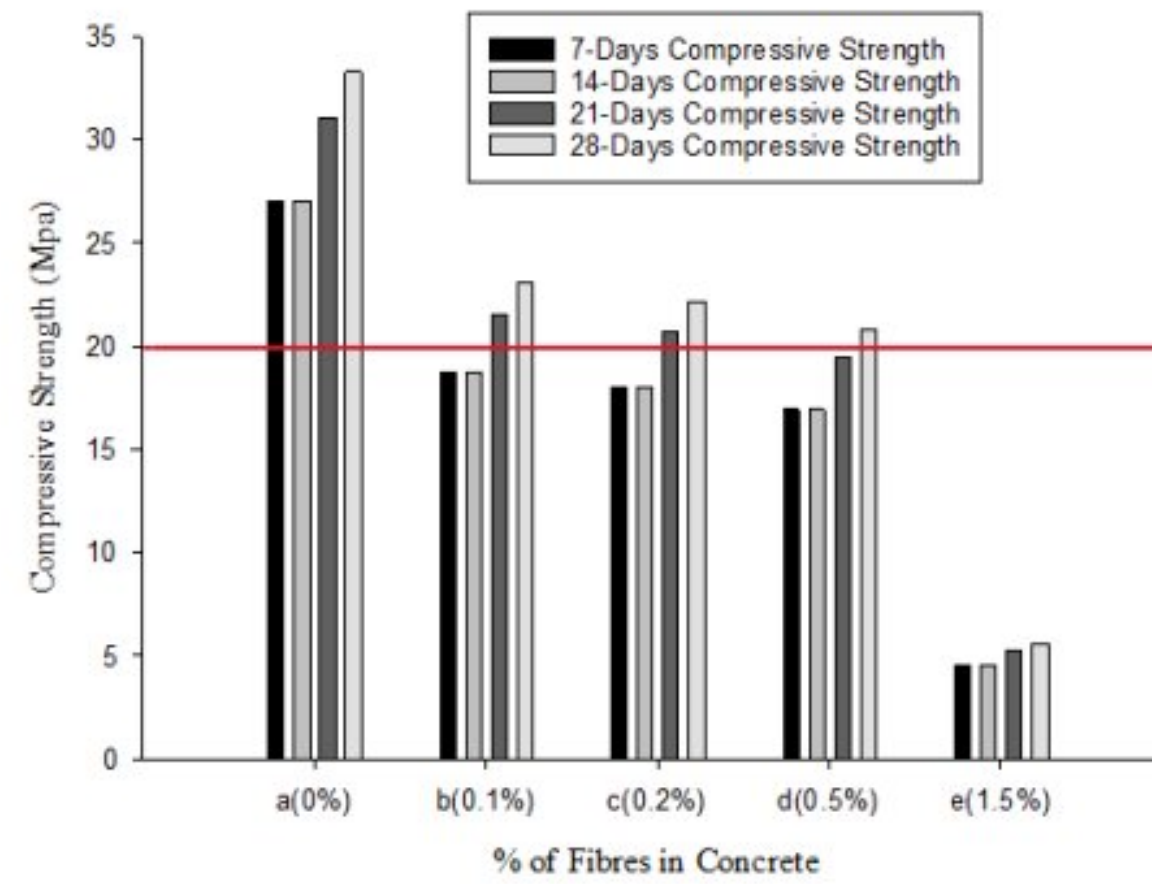


Figure 4.4 Compressive strength of pine needle fibre reinforced concrete with varied fibres. The red line indicates the target mean compressive strength

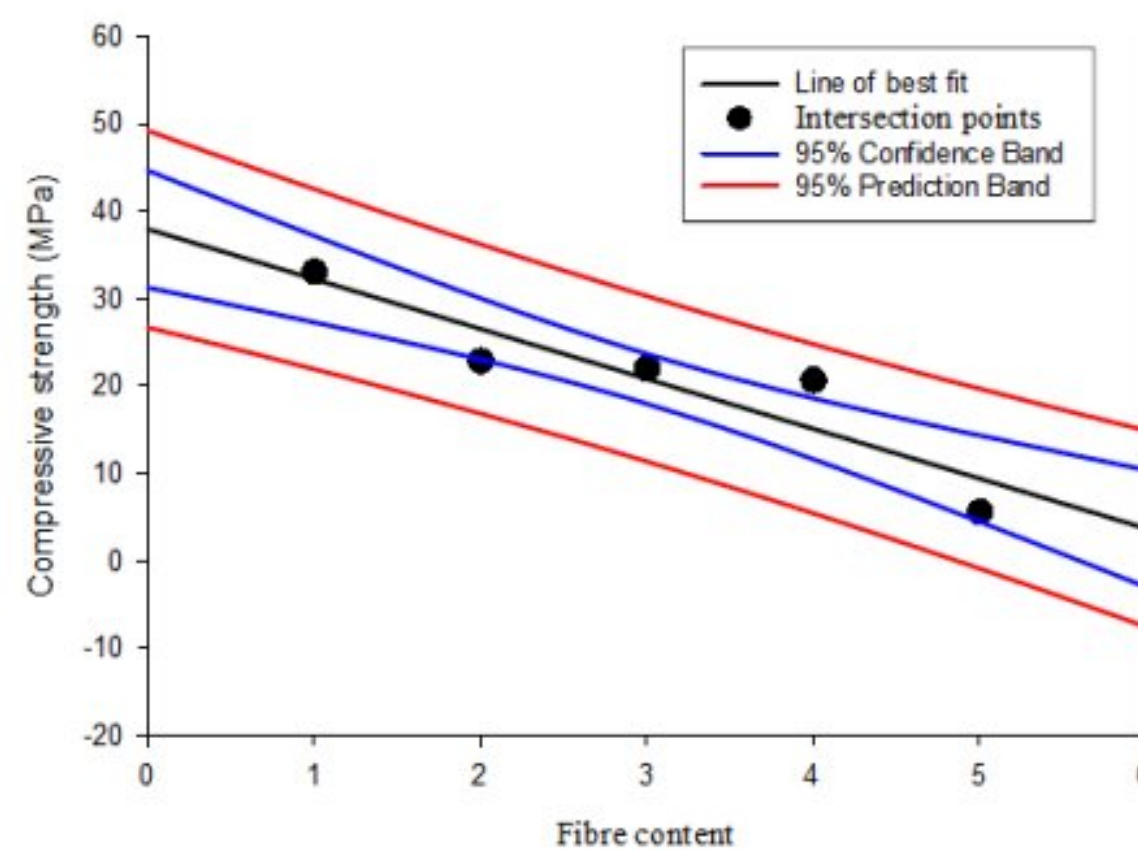


Figure 4.5 Relationship between pine needle content and concrete compressive strength.

The Figure 4.4 illustrates the relationship between pine needle fibre dose and compressive characteristic strength as determined by regression analysis as prediction model. The negative slope of the curve indicates that as pine needle fibre content increases, compressive strength decreases. This inverse relationship suggests that the inclusion of

the pine needle fibre doses into the mixture has a detrimental impact on the compressive characteristic strength of the concrete.

From [Figure 4.4](#), the linear regression model (in which f_{ck} is the predicted value of the compressive characteristic strength and x is the independent variable representing the pine needle fibre content) generated shows $R^2 = 0.84217$. The regression analysis revealed a highly significant relationship between pine needle fibre content and compressive strength ($P < 0.0001$). The R-square value of 1.0 indicates that the model almost explains all the variations in compressive strength. The negative slope of the curve confirms that the increasing pine needle fibre content leads to a reduction in compressive characteristic strength.

$$f_{ck} = 37.91 - 5.71x \quad \text{Eq. (4.1)}$$

4.3.2 Compressive strength of sisal fibre-reinforced concrete

Assessing the compressive strength of concrete is a fundamental step in evaluating its mechanical behaviour and structural integrity. By subjecting the composite material into controlled compressive loading, this test provides critical information on the materials capacity to resist deformation and failure under loading conditions. The outcome of the compressive characteristic examination is essential in determining the suitability of concrete for various applications. Thus, this investigation focuses on evaluating the compressive characteristic strength of the sisal RC with the aim of determining its potential applications. The results are shown in [Figure 4.6](#) and [Figure 4.7](#).

The compressive characteristic strength-ability of sisal fibre-reinforced concrete was evaluated at various fibre proportions (0%, 0.1%, 0.2%, 0.5% and 1.5% by weight). The control experiment (0% fibre) exhibited increasing compressive strength with time,

reaching 33.32 Nmm² on the 28th day, exceeding the target class 20 N/mm² strength. The increased add of extra sisal fibre into the concrete led to a decrease in compressive strength, with higher fibre proportions resulting in greater reductions in compressive strength. The 0.1% fibre proportion showed a 28th-day compressive strength of 27.2 N/mm², representing an 18.4% decrease compared to the control experiment, yet still surpassing the target strength. The 0.2% fibre proportion yielded similar results, with a 28th-day compressive strength of 26.95 N/mm², indicating a 19.1% decrease. Some of the observed concrete strength exceeded the design strength possibly due to the optimal curing conditions, high material quality, or due to variation in the material proportioning during mixing process or batching.

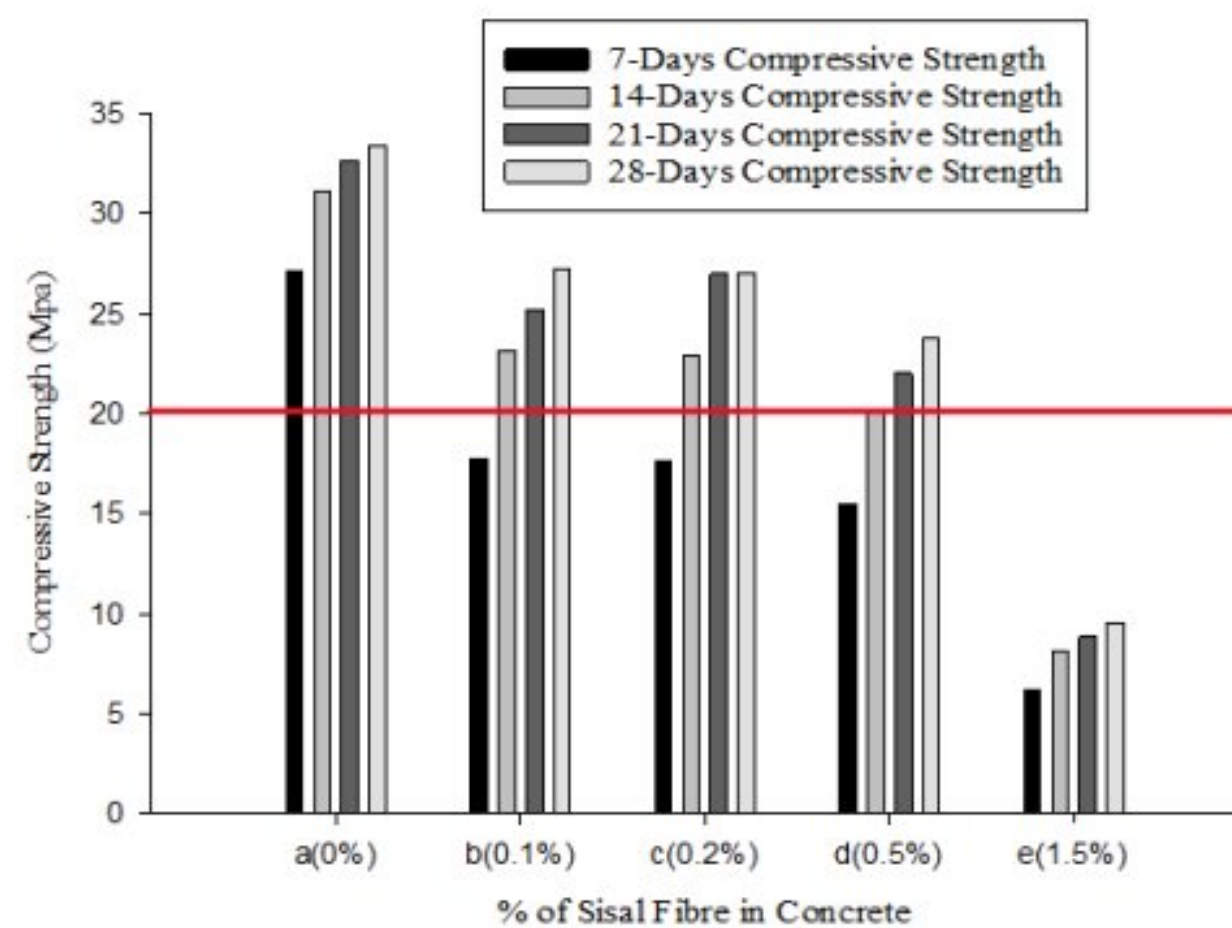


Figure 4.6 Compressive strength of sisal fibre-reinforced concrete

The red line in Figure 4.6 represents the target compressive strength of concrete.

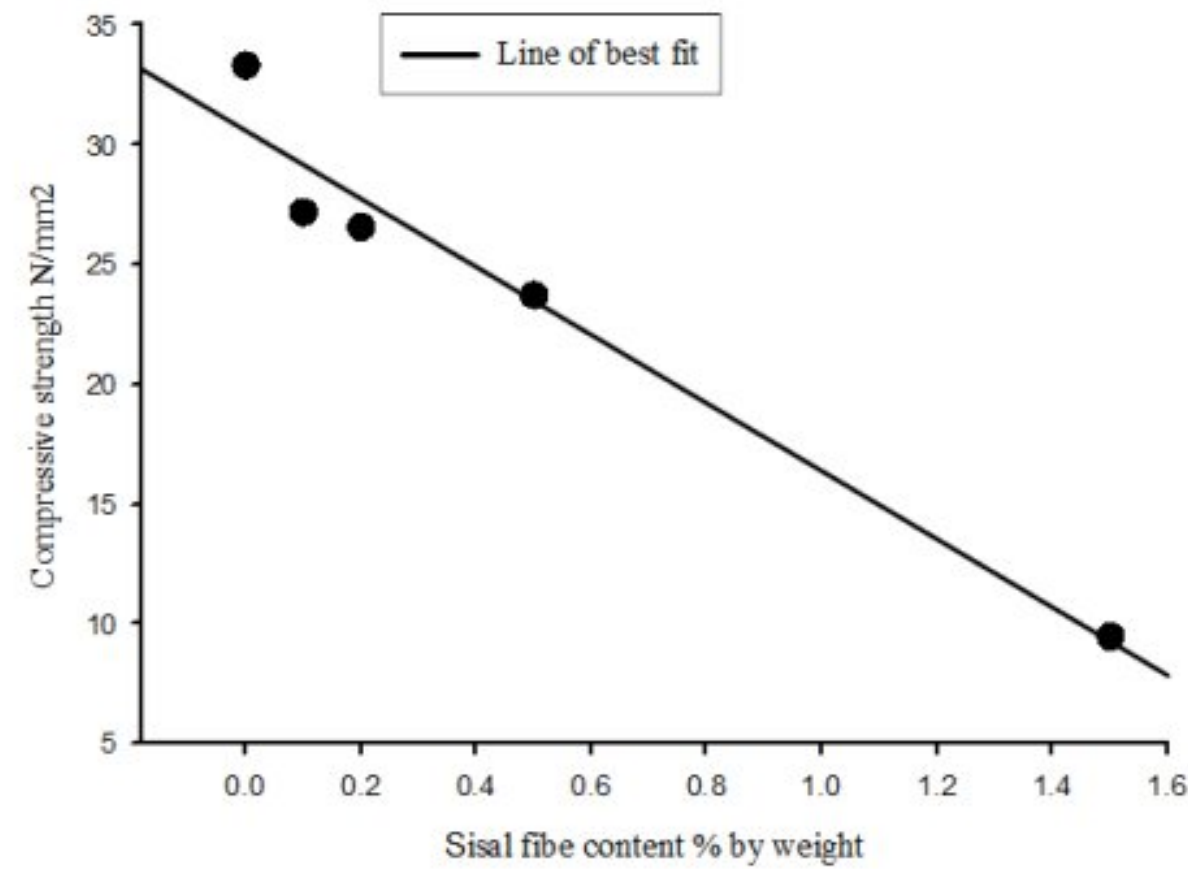


Figure 4.7 Compressive strength of fibre-reinforced concrete

Further increase in fibre proportion (0.5% and 1.5%) resulted in more significant reductions in compressive strength, with 28th-day values of 23.73 N/mm² (28.8% decrease) and 9.49 N/mm² (71.5% decrease), respectively. Notably, the 0.5% fibre proportion still achieved the target class 20 strength, while the 1.5% proportion fell short. Based on the results, the optimal proportion proportions of sisal fibres that maximizes impact on strength properties of concrete while potentially offering benefits in terms of tensile characteristic strength, ductility, and resistance to cracks. The single pine needle fibre reinforced concrete of ratio 0.1% fibre performed more with a compressive strength of 26.2N/mm² compared to the composite concrete material with 0.2% each combined fibres, which yielded a compressive strength of 23.7N/mm².

In conclusion, the evaluation findings indicate that the increased inclusion of the sisal fibres generally reduces compressive strength with higher fibre proportions leading to greater losses. The loss in compressive characteristic strength could possibly be as a result of the fibre congestion which reduces workability hence reducing the interfacial bonding between the fibres and concrete matrix (Mukil et al., 2024). However, (0.1%-

0.2%) may offer balance between strength and potential benefits in other properties while still meeting the target class strength of 20 N/mm².

Sisal fibre addition reduces compressive strength, with higher proportions leading to greater losses. The optimal proportions of sisal fibres appear to be around 0.1% - 0.2% by weight. Fibre proportions up to 0.5% can still achieve the target class 20N/mm². The Figure 4.8 illustrates the detailed relationship and correlation between the sisal-material fibre and the compressive characteristic strength of concrete. From the figure 27, generated from the regression model, $R^2 = 0.1126$, the equation of regression analysis is:

$$f_{ck} = 15.23 + 2.41 \quad \text{Eq. (4.2)}$$

Equation 4.2 is a proposed linear equation for estimating the compressive strength of concrete, where f_{ck} is the characteristic strength for concrete and x is the fibre content variable. A strong correlation was found between sisal fibre proportion and compressive strength with a correlation coefficient R of (0.9649).

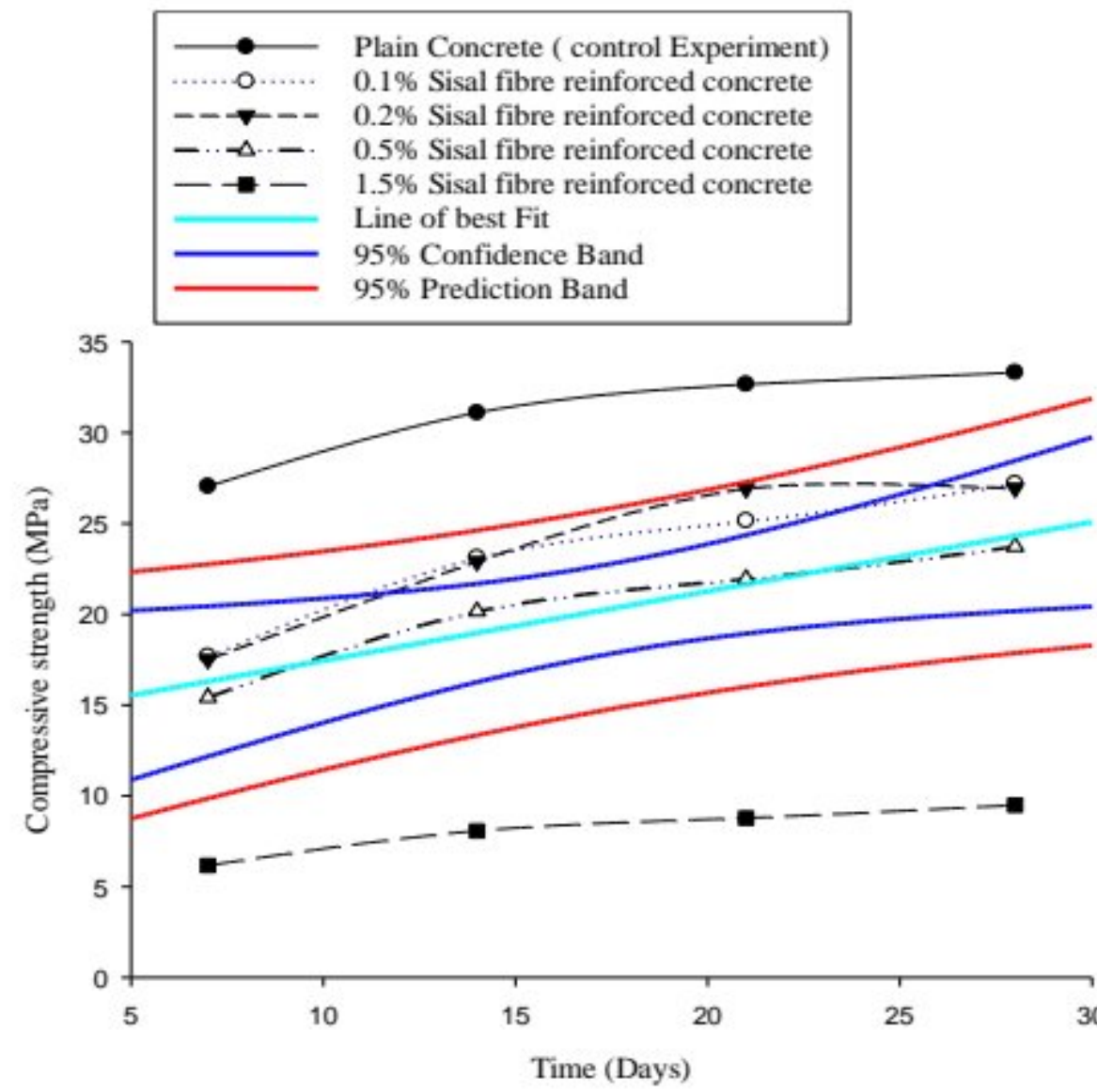


Figure 4.8 Relationship between sisal fibre content and concrete compressive strength

4.3.3 Compressive strength of pine needle-sisal reinforced concrete

As discussed in Section 3.6.1, to investigate the combined effect of hybrid fibre contents on concrete strength properties, focusing on the potential enhancements in mechanical properties and sustainability, several fibre proportions were used to formulate different specimens. The results are discussed below and key findings elaborated with graphical illustrations (see Figure 4.9).

A mixture of fibre hybrid proportions was examined with the proportions of 0%, 0.2%:0.2%, 0.5%:0.5%, 0.5%:1%, 1%:0.5% by weight, sisal to pine needle fibres respectively. The compressive characteristic behavioural strength of all concrete mixtures went up with the curing age, which is consistent with the expected behaviour of concrete as it matures (Gao et al., 2025).

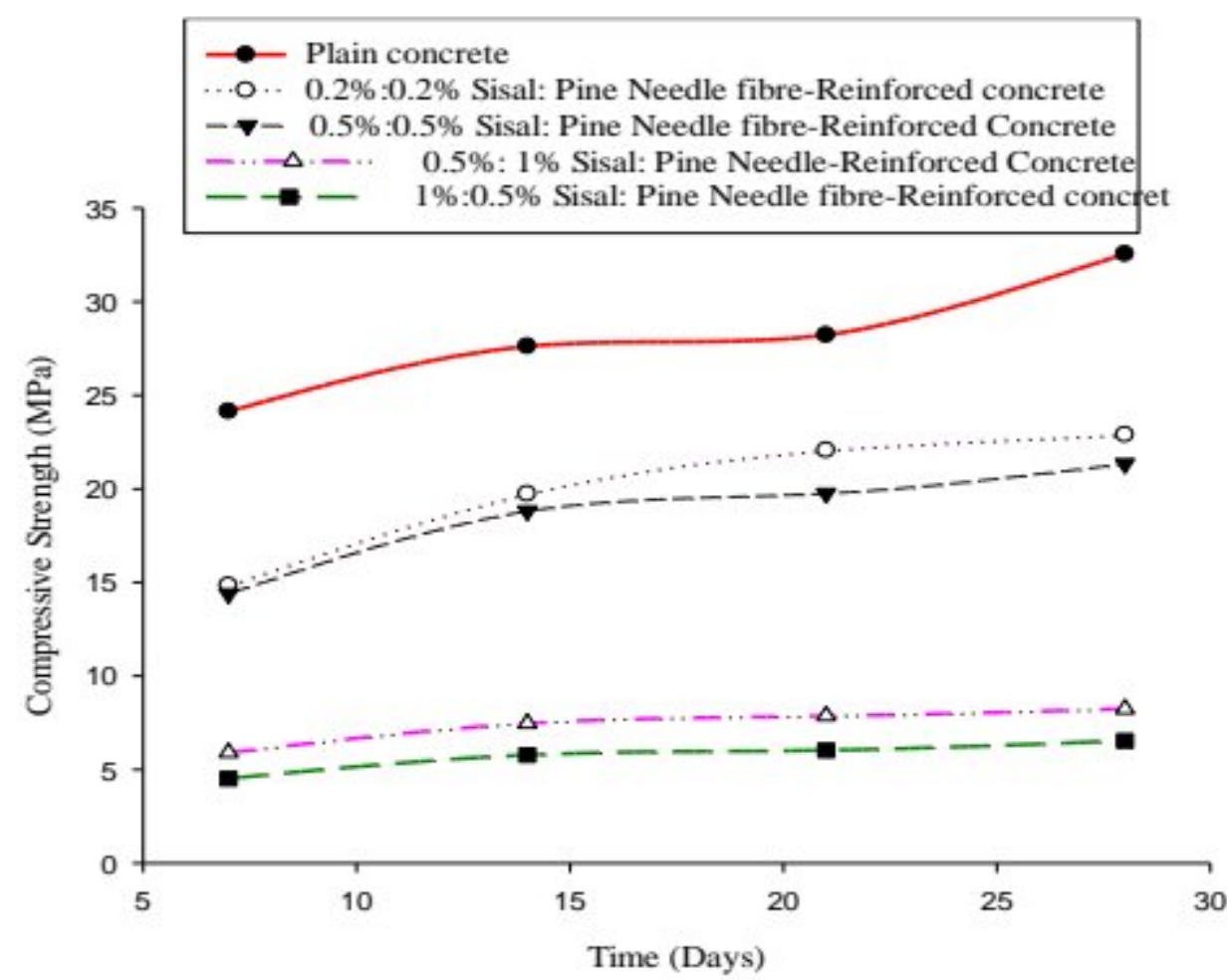


Figure 4.9 Relationship between sisal fibre content and concrete compressive strength

However, the addition of more fibre contents generally led to a fall in the compressive strength of concrete compared to the control sample (32.55 N/mm² at 28days), with the magnitude reduction depending on the fibre proportion. Notably, the 0.2%:0.2% fibre reinforced concrete gained 22.89 N/mm², a 0.5%:0.5% fibre reinforced

concrete gained 21.34 N/mm², 0.5%:1% gained 8.25 N/mm² and 1%:0.5% proportion gained 6.54 N/mm² compressive strength, all at the ratio of sisal: Pine needle fibres respectively at 28days age.

The compressive strength percentage decrease was 29.7%, 34.4%, 74.4% and 79.9% respectively with addition of more fibre contents beyond the optimal proportions. This could be because of the increased porosity caused by large fibre contents and reduced workability, possibly induced by inadequate bonding character between the concrete matrix and the fibres-matrix. This is in line with the recent research trends which specify that for compressive strength, the fibre content must not be too high ([Hamada et al., 2023](#)).

4.3.4 Comparison of the impact of hybrid fibre contents on compressive strength

A compressive investigation was undertaken to assess the relative merits of hybrid fibres, sisal fibres and pine needle fibres in augmenting the performance of the NFRC. This comparison looked deeply into on the distinct impacts of each fibre type on the strength property of concrete, providing valuable insights into their potential applications. The findings are visually represented in

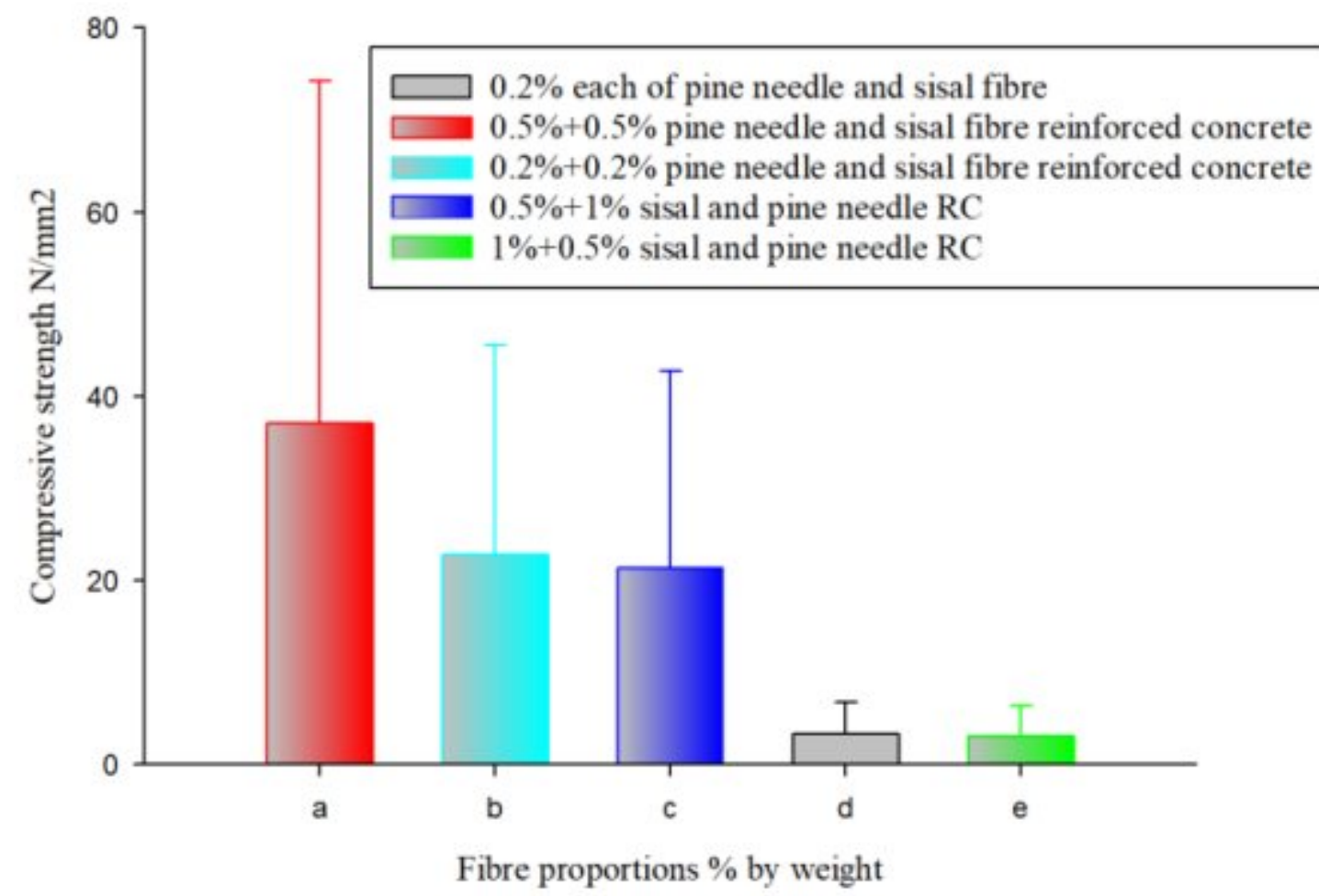


Figure 4.10 Compressive strength of pine needle and sisal fibre reinforced concrete

The addition of hybrid fibres (sisal and pine needle fibres) to the concrete mix brought about the reduced compressive characteristic strength compared to plain concrete (32.55N/mm^2). The strength reductions range between 31.4% and 79.9%, with the highest strength of 22.32 Nmm^2 achieved 0.2% sisal and 0.2% pine needle fibre contents. Increasing the fibre proportions caused a significant fall/reduction in compressive characteristic strength, possibly due to increased porosity in the concrete composite, causing reduced workability and compaction. Additionally, this could be caused due to fibre dispersion, fibre agglomeration hence creating weak joints in the concrete (Hassan and Saeed, 2024).

4.3.5 Flexural strength of pine needle and sisal reinforced concrete composite

The flexural test is a key indicator of concrete's real potential to stand against cracking and failure under bending loads. The test examines the flexural performance of hybrid fibre RC, shedding light on synergistic effects of these hybrid fibres, providing insights into potential to construct the longevity and structural potential of the NFRC composite. Flexural examination is a fundamental assessment mechanism used to find the mechanical characteristics of materials subjected to bending stresses. By applying controlled

loads to specimens, researchers can gain valuable key insights into material characteristic to resist bending failure.

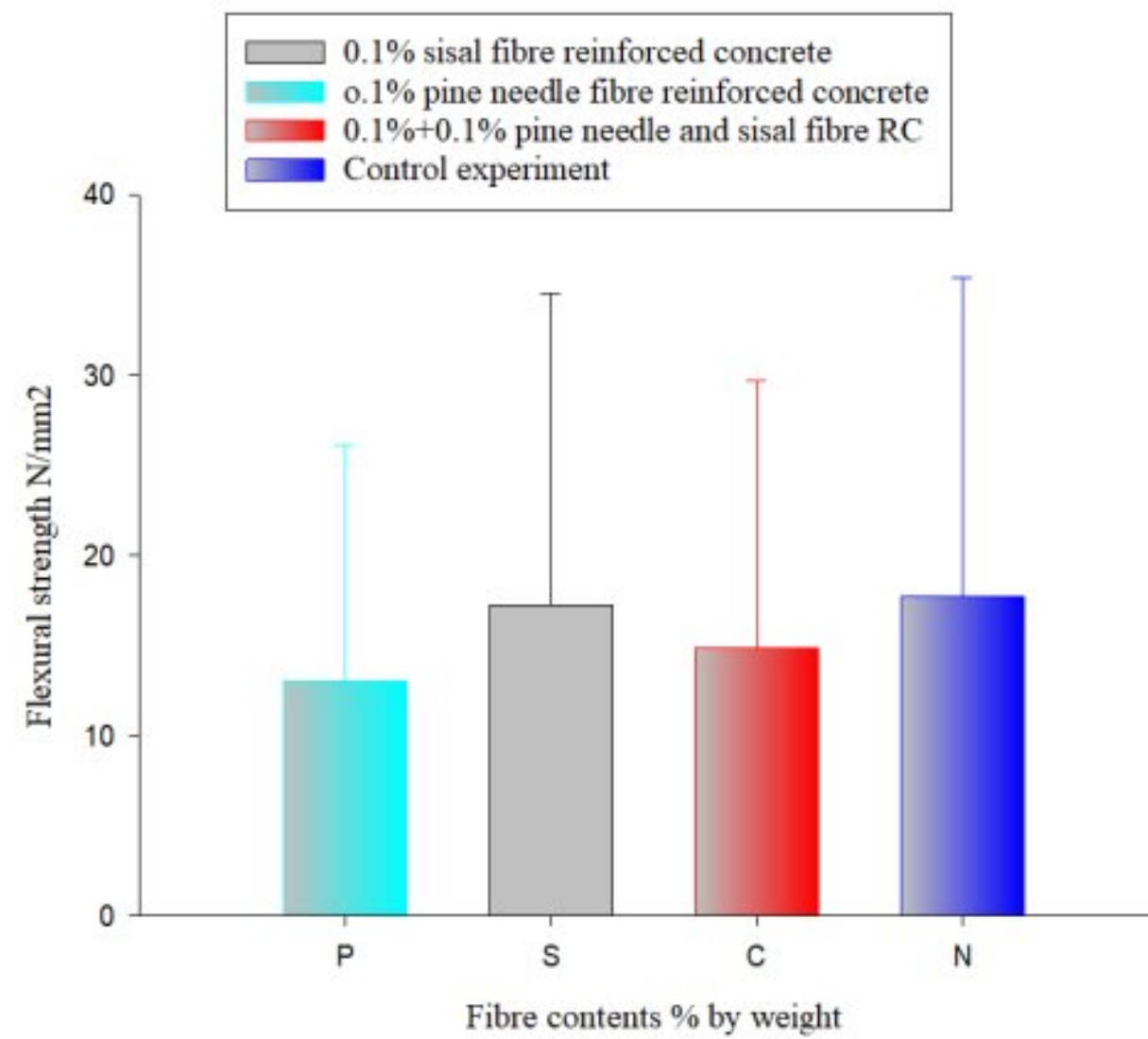


Figure 4.11 Flexural strength of pine needle and sisal fibre reinforced concrete.

The flexural test results as shown in [Figure 4.11](#) indicate that the inclusion of 0.1% pine needle fibres led into a significant fall in flexural characteristic strength of 26.3% compared to plain concrete. In contrast, the addition of 0.1% sisal fibre resulted in the least decrease in flexural strength of 2.5%, the hybrid composite consisting of 0.1% pine needle fibres and 0.1% sisal fibres showed a flexural strength value that was 16.1% lower than the pine needle fibre reinforced concrete.

The reduction in flexural strength could be related to the potential weak bonding character in between the natural fibre matrix and the concrete, caused by fibre congestions leading to reduced load bearing ability of the hybrid material ([Hussein et al., 2023](#)). The results suggest that sisal fibres are more suitable for concrete use compared pine needle fibres at a 0.1% dosage, potentially due to better dispersion and interfacial bonding within the concrete matrix. The combination of pine needle and sisal fibres did

not appear to yield a synergistic effect on flexural strength at the tested dosages. However, their performance show improvement compared to pine needle fibre reinforced concrete.

4.3.6 Split tensile strength test

The tensile characteristic strength results of concrete mixtures incorporating pine needle and sisal fibres revealed interesting trends. The plain concrete without any fibre exhibited a tensile strength of 2.21 N/mm^2 . Putting more fibres into the concrete mixture ignited the increase in the tensile characteristic strength up to a certain point, with the highest tensile strength of 2.39 N/mm^2 achieved at a sisal fibre content of 0.2%, representing an 8.1% increase compared to the neat concrete. However, further increase in sisal fibre content led to a decrease in tensile strength dropping to 2.12 N/mm^2 at 0.5% sisal fibre content, 1.56 N/mm^2 at 1.5% sisal fibre content, and 0.20 N/mm^2 at 2% sisal fibre content. This stands for a significant fall of 90.9% of tensile strength at the highest fibre content.

Similarly incorporating pine needle fibres into the concrete mixture also increased the tensile strength up to a certain point. The highest tensile strength of 2.69 N/mm^2 was achieved at a pine needle fibre content of 0.2%, representing a 21.7% increase compared to the plain concrete. However, the continued increase in pine needle fibre amounts led to a significant decrease in tensile characteristic strength dropping to 1.67 N/mm^2 at 0.5% pine needle fibre content, and 0.42 N/mm^2 at 2% pine needle fibre amount as shown in [Figure 4.12](#).

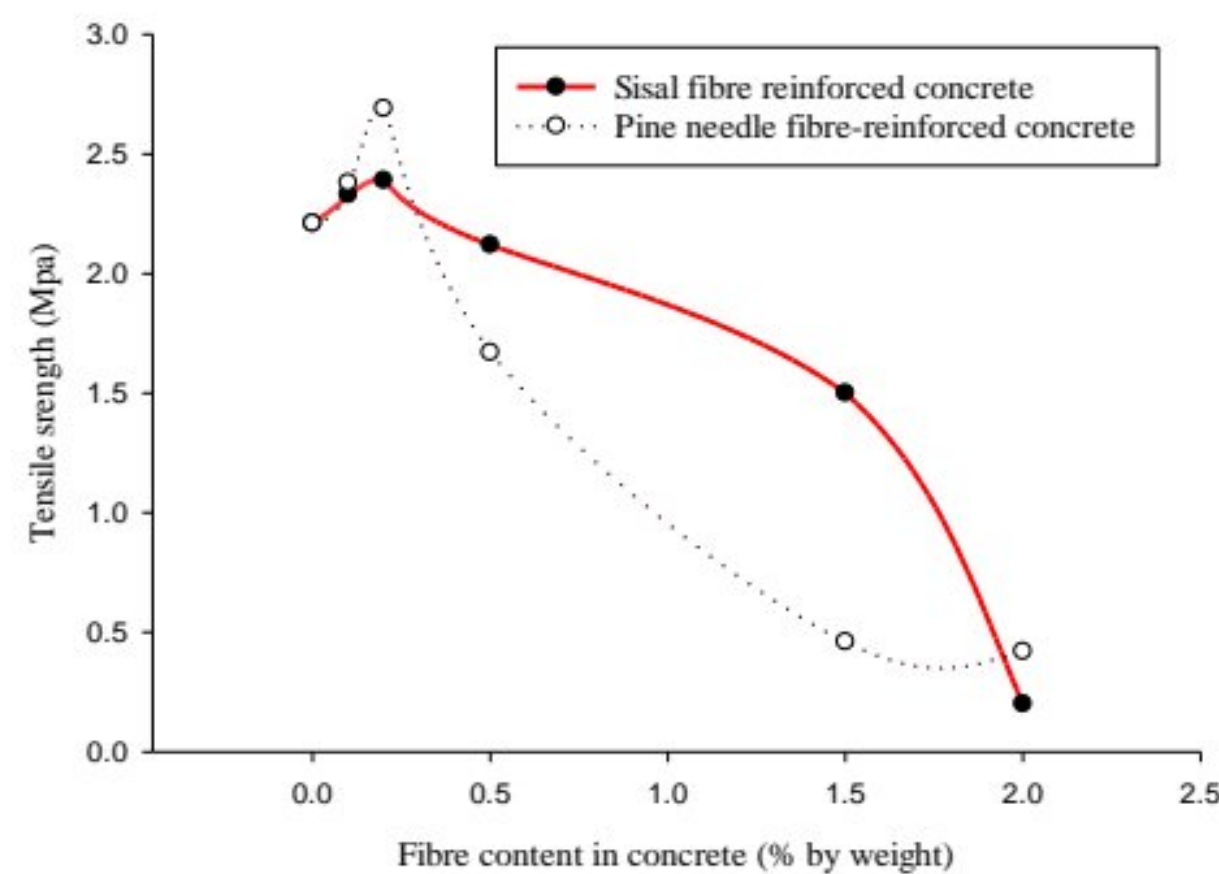


Figure 4.12 Split tensile strength of pine needle and sisal fibre-reinforced concrete

The composite material with 0.1% sisal fibres and 0.1% pine needle fibres exhibited a tensile strength of 2.24 N/mm^2 , which is slightly greater than the neat concrete but lower than the individual fibre reinforced concretes with similar fibre contents.

The observed behaviours in tensile characteristic strength can be related to the complex interactions between the fibre-body and the concrete matrix. At optimal fibre contents, the fibres appear to effectively reinforce the concrete, leading to improved tensile strength. However, at greater fibre amounts, the fibres may agglomerate, leading to increased porosity and weakened concrete matrix, ultimately resulting in reduced tensile strength (see Figure 4.13–

Figure 4.15). The results also suggest that pine needle fibre reinforced concrete offers more tensile strength with an optimal fibre proportion of 0.2% compared to sisal FRC, (pine needle and sisal fibre) RC composite.

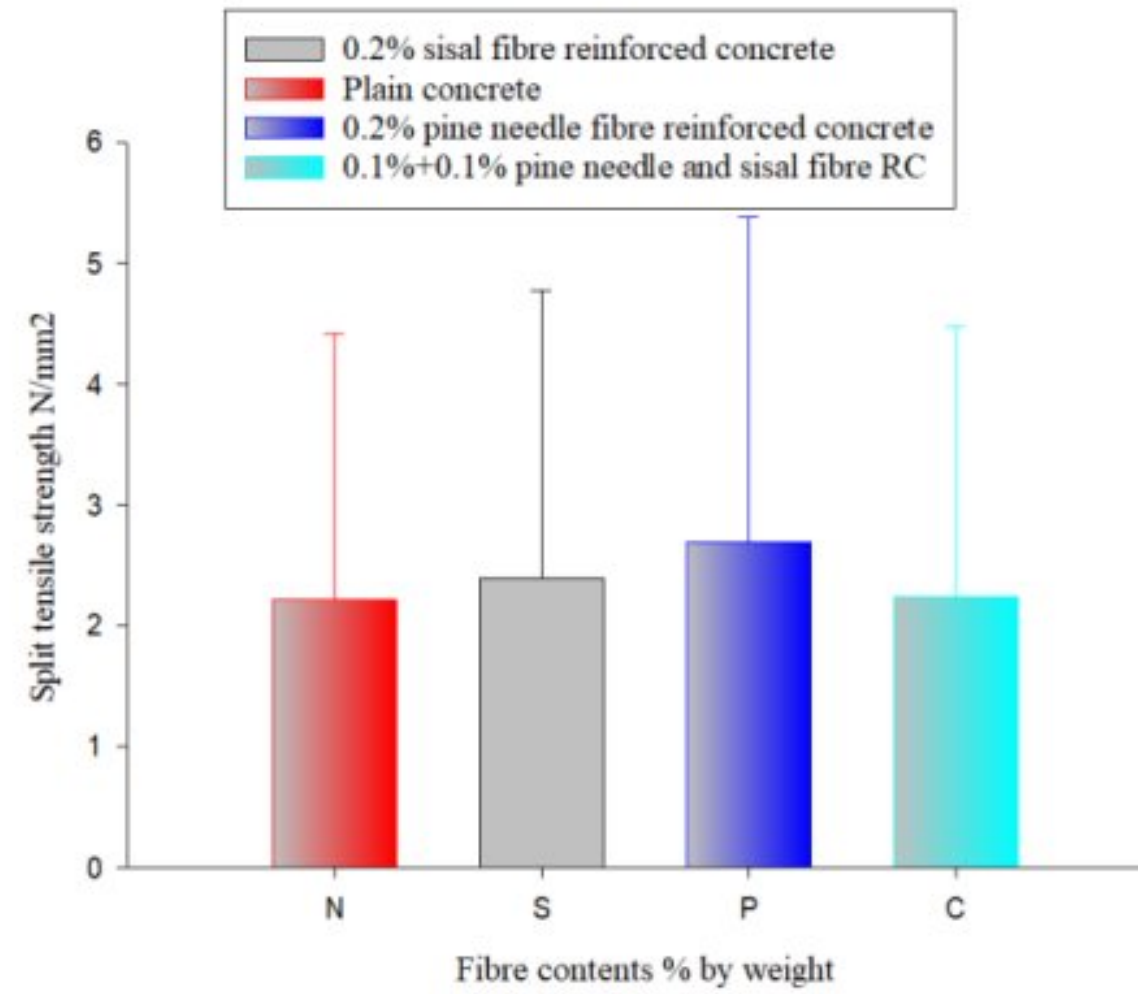


Figure 4.13 Split tensile strength of concrete composite

4.3.7 Prediction model for tensile strength

A prediction model was developed to estimate tensile strength based on fibre proportion as shown in Figure 4.14. The model is valid for fibre proportions ranging from between 0 and 2% by weight and predicts tensile strength between 0.42 and 2.21 Nmm² with. The Y-intercept is statistically significant (t-value;13.2568, p-value: 0.0002).

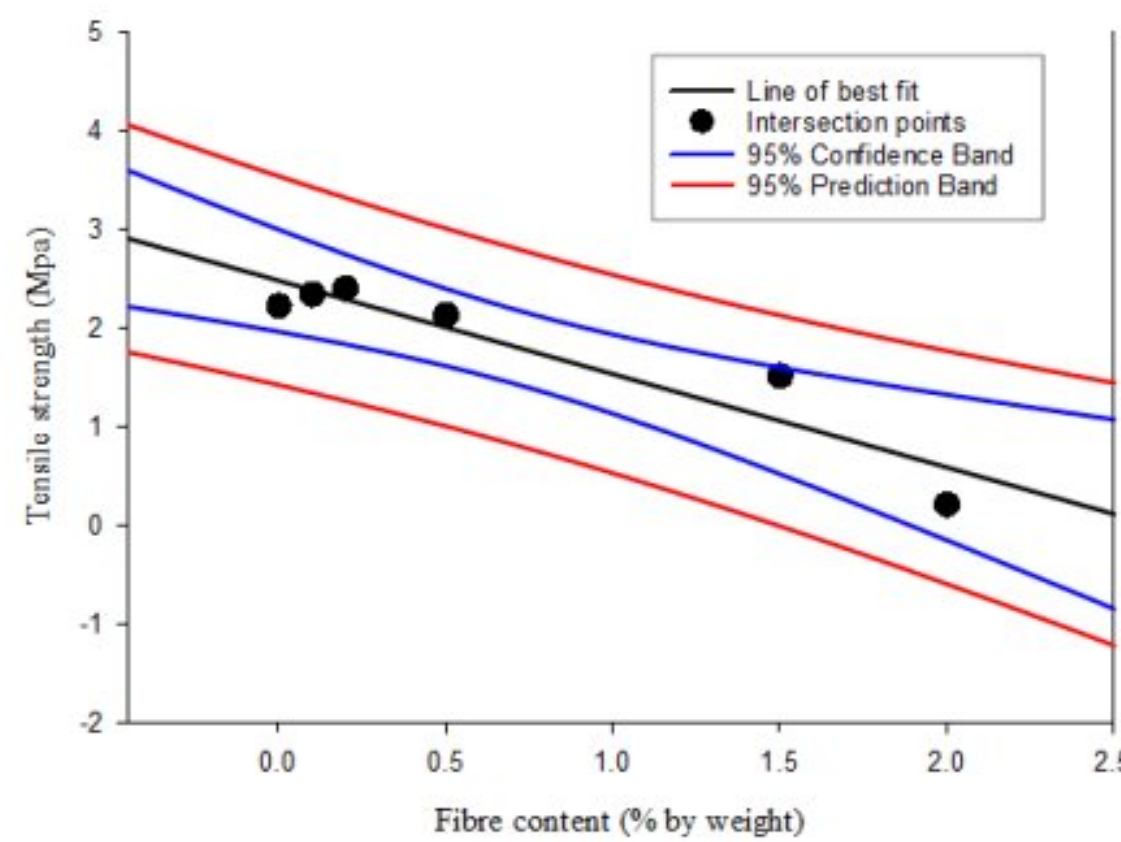


Figure 4.14 Prediction model graph for tensile strength

The Eq. (4.3), in which f_{ck} is the estimated tensile strength and x is the fibre content, can be used to estimate the variables within a significant range of values. The equation

4.3 can be used to estimate the fibre contents or split tensile characteristic strength for pine needle fibre RC.

$$f_{ck} = 2.47 - 0.9466x \quad \text{Eq. (4.3)}$$

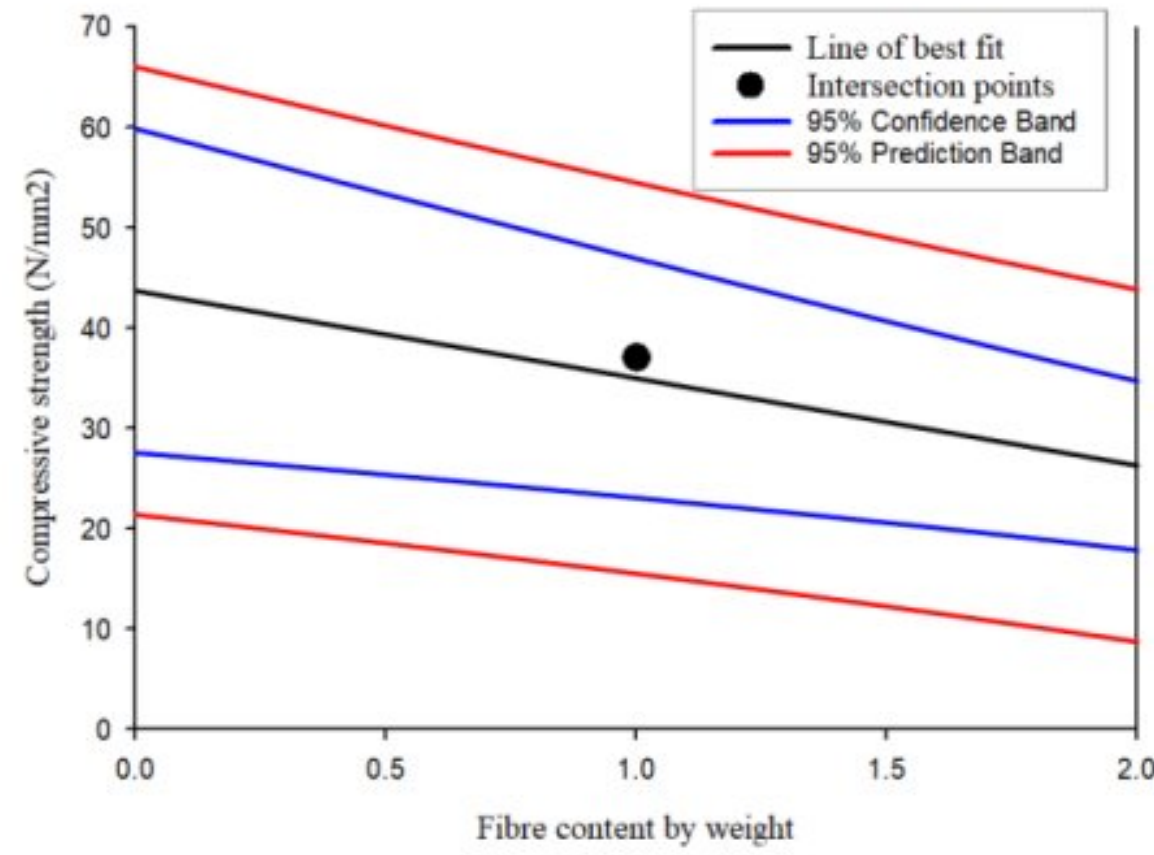


Figure 4.15 Split tensile strength of concrete composite

The composite concrete material was analysed using regression model analysis and the results show a strong correlation between the variables with P value of 0.0033, indicating a statistical significance in fibre type and content and high accuracy indicated by an R^2 value of 0.9153. Indicating that 0.2% fibre each by weight had a better compressive characteristic strength of 23N/mm^2 compared to the composite with the highest fibre ratio of 1% pine needle fibre and 0.5% sisal fibre which yielded a 3.4N/mm^2 . The analysis showed that the composite material with optimum fibre ratios yielded larger compressive characteristic strength when related to the composite with higher fibre proportions. The composite revealed more or less the same strength as compared to each single fibre reinforced concrete with a variation of about $\pm 3\text{N/mm}^2$. However, its performance was less than that of a single sisal fibre RC.

4.3.8 External data comparison and validation process

External validation and or comparison is a critical evaluation step for regression models, where the model's performance is assessed on a separate independent dataset (Mansmann and Ön, 2025). This process verifies the model's ability to generalize and make accurate predictions beyond research data. The predictive capability of the developed regression model (see Figure 4.14) was assessed using a dataset sourced from another research study, by applying the model to this distinct dataset, its versatility and accuracy were evaluated.

To validate the regression model used and the equation developed in this study, the results were compared with the data from a previous study on coir fibre-reinforced concrete (Seneviratne et al., 2017). The dataset was first synthesized, analysed and comparison made by plotting both datasets on the same graph, which showed a good match between the two. The model's predictions for specific fibre contents were made and plotted in conjunction with the original data, revealing a strong correlation and consistent trend. The estimations generated using the model were compared to the other researcher's data, this gave real values contained in the dataset, revealing the reliability of the model. This validation step provided further evidence of the model's potential-ability and suitability for broader and or larger application.

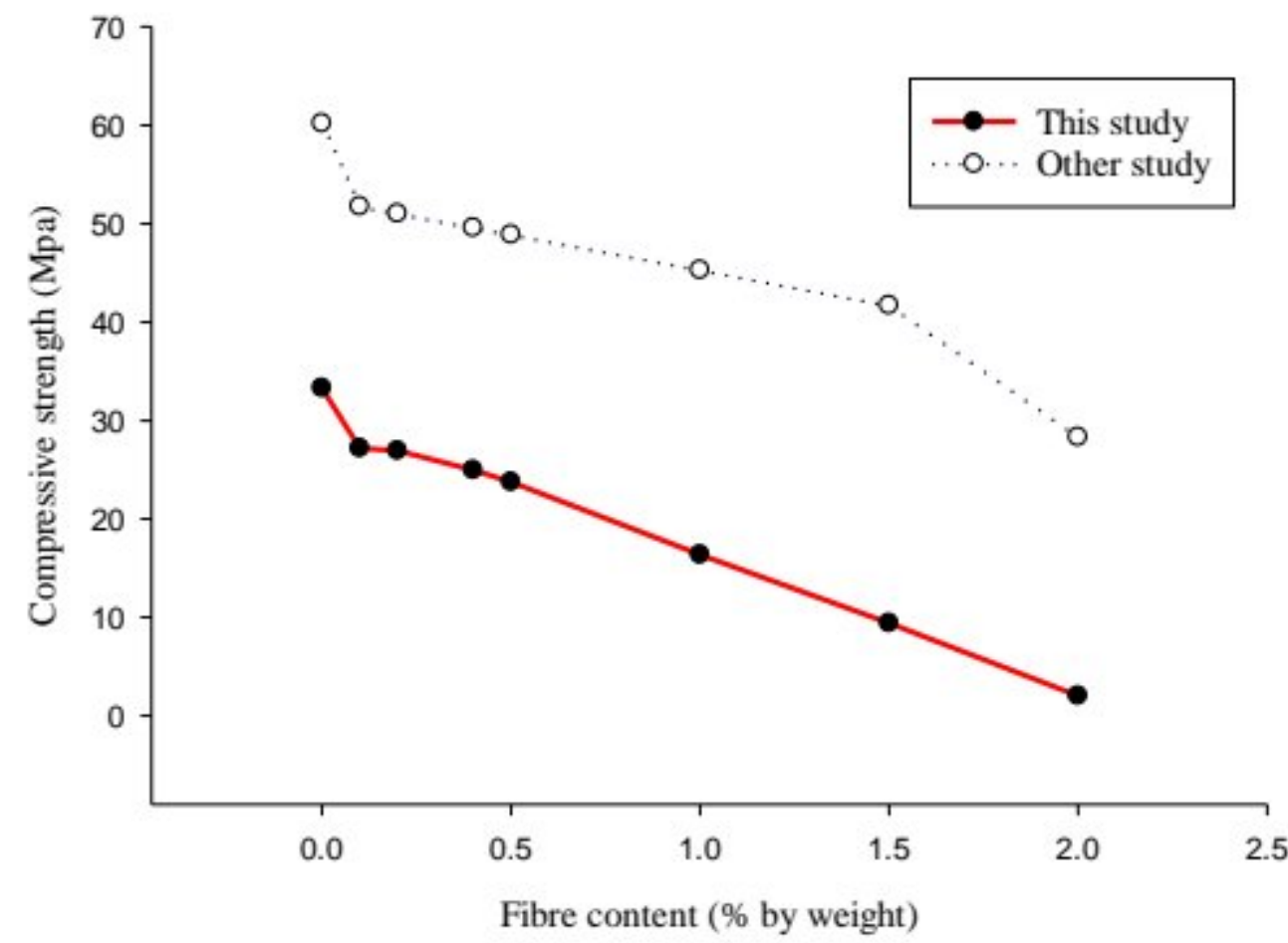


Figure 4.16 comparison of data with another researcher's data

The analysis showed that addition of fibres in concrete triggered a fall in compressive characteristic strength for both studies, despite the difference in fibre types (sisal fibres verses coir fibre). The good agreement between the two datasets and the successful application of the regression model to other researcher's data provide strong evidence for the validity and robustness of the model. This external validation demonstrates that the model could be incorporated in the analysis and prediction of the strength properties of NFRC.

4.3.9 Analysis of variance to test statistical significance (ANOVA)

To evaluate the effects of fibre type, and dosage on the strength properties of concrete, a statistical analysis was undertaken using analysis of variance (ANOVA). This approach enables the examination of the individual and combined influences of fibre type, including sisal and pine needle, and varying content levels on the resulting strength characteristics of concrete. The outcomes of the analysis are presented and discussed offering significant insights into the factors that shape the strength properties of fibre reinforced concrete (see [Table 4.3](#)).

Table 4.3 Analysis of variance (ANOVA) in the perceived strength differences

Source	DF	SS	MS	F-value	P-value
Fibre type	2	124.45	61.72	5.23	0.012
Content	3	456.45	156.26	12.91	0.0001
Interaction	6	78.9	13.15	1.11	0.372
Error	24	283.11	11.80		

The analysis of variance ANOVA results reveal that fibre type and dosages significantly influence the compressive strength of concrete. The fibre type has statistically significant effect on the compressive strength of concrete, as indicated by a P-value of 0.012. This suggest that the type of fibre used, whether sisal, pine needle, or a combination, plays a role in determining the concretes strength, this agrees with studies by [Ali et al. \(2018\)](#) and [Kumar & Jain \(2020\)](#), who reported that fibre type and its contents greatly influence the mechanical behaviour of fibre-reinforced concrete composites due to

differences in fibre morphology, tensile strength, and bonding characteristics with the cement matrix.

There is no significant interaction between the fibre type and dosage, as evidenced by the P-value of 0.372, meaning that the effect of fibre type on compressive strength is consistent across different content levels. The total variability in compressive strength attributed to fibre type difference is represented by a sum of 123.45 and the average variability in compressive strength is denoted by a mean square (MS) of 61.72. a sum of squares (SS) of 456.78 represents the total variability in compressive strength attributed to dosage level differences. The average variability in compressive strength per dosage comparison is indicated by a mean square (MS) of 152.26.

In general, the results highlight that the importance of fibre type and dosage in determining the strength characteristic of concrete, with contents, exhibiting a more pronounced effect. Both the pine needle and sisal fibres respond similarly to changes in dosage levels, with no strong synergistic positive effect on the concrete strength properties when combined as composite material. The study concludes that sisal fibre concrete exhibits slightly higher strength performance than pine needle fibre concrete possibly due to better bonding and stress-bridging capacity and its exhibition of high tensile strength compared to pine needle.

4.4 Durability of pine needle and sisal fibre-reinforced concrete composite

The capacity of concrete to withstand the environmental stresses is crucial for either its short- or long-term performance ([Krelani et al., 2025](#)). This segment of the study investigates the durability properties of concrete composites containing pine needle and sisal

fibres, specifically evaluating their water absorption and corrosion resistance characteristics, to elucidate the potential advantages of utilizing these natural fibres in concrete applications.

4.4.1 Water absorption test

The test of conducted to evaluate the water absorption degree of NFRC is a critical as the assessment mode of concrete's durability, providing insights into its pore structure and susceptibility to water ingress. By quantifying the amount of water absorbed over time, this test assists us to evaluate the concrete resistance to degradation and potential damage to exposure, especially such concrete improved with natural fibres. The results shown in [Table 4.4](#) can inform the development of more durable and sustainable concrete mixtures.

Table 4.4 Water absorption for concrete with pine needle and sisal fibre composites

Concrete type	Fibre content (%)	Absorption (%)
Plain concrete	0	8.2
Sisal fibre reinforced concrete	0.5	9.5
Pine needle fibre reinforced concrete	0.5	9.0
Sisal fibre reinforced concrete	2	12.5
Pine needle fibre reinforced concrete	2	12.4
Pine needle and sisal fibre reinforced concrete	0.5:0.5	10.5

The findings of the water absorption examination test results portrayed the consideration of natural fibres into the concrete raised its water absorption, with the rate of absorption changing basing on the fibre type and its content. The plain concrete had the lowest water absorption, whereas, the increment of 0.5% fibre amounts triggered a slight rise in water absorption. This could be because of the increased porosity caused

by the excess fibre content, leading to water flows through the concrete composite, possibly impacting into its durability.

Notably, increasing fibre content to 2% significantly increased water absorption for both fibres to 12.5% for sisal fibre reinforced concrete and 12.4% for pine needle fibre reinforced concrete. In contrast, a hybrid combination of 0.5% sisal and 0.5% pine needle fibres yielded a water absorption of 10.5% which fell within the rates of individual fibres. This could be because of the synergistic impact of the two fibres, the interlocking of the fibres due to their difference in fibre diameter, closing up the gaps and reducing the water percolation through the composite.

4.4.2 Pine needle and sisal fibre RC degradation test (Durability test)

Assessing the alkaline resistance of NFR concrete is important for predicting the lifespan of reinforced concrete structures. This test examines the natural fibre concrete's ability to shield steel reinforcement from alkaline destructive environmental agents, providing key insights into its durability and potential vulnerability to degradation. By investigating the alkaline-degradation resistance of pine needle and sisal fibre reinforced concrete, researchers can gain a deeper understanding of its performance under such environmental conditions.

The degradation test results in [Table 4.5](#) indicate that, the pine needle and sisal fibre reinforced concrete, exhibit good resistance properties to alkaline caused degradation in a simulated environment (10%-concentrated sodium hydroxide solution). Only sample surface colour slight change was observed, minor signs of stains with no degradation in the internal fibres RC.

Table 4.5 pine needle and sisal fibre reinforced concrete degradation test results

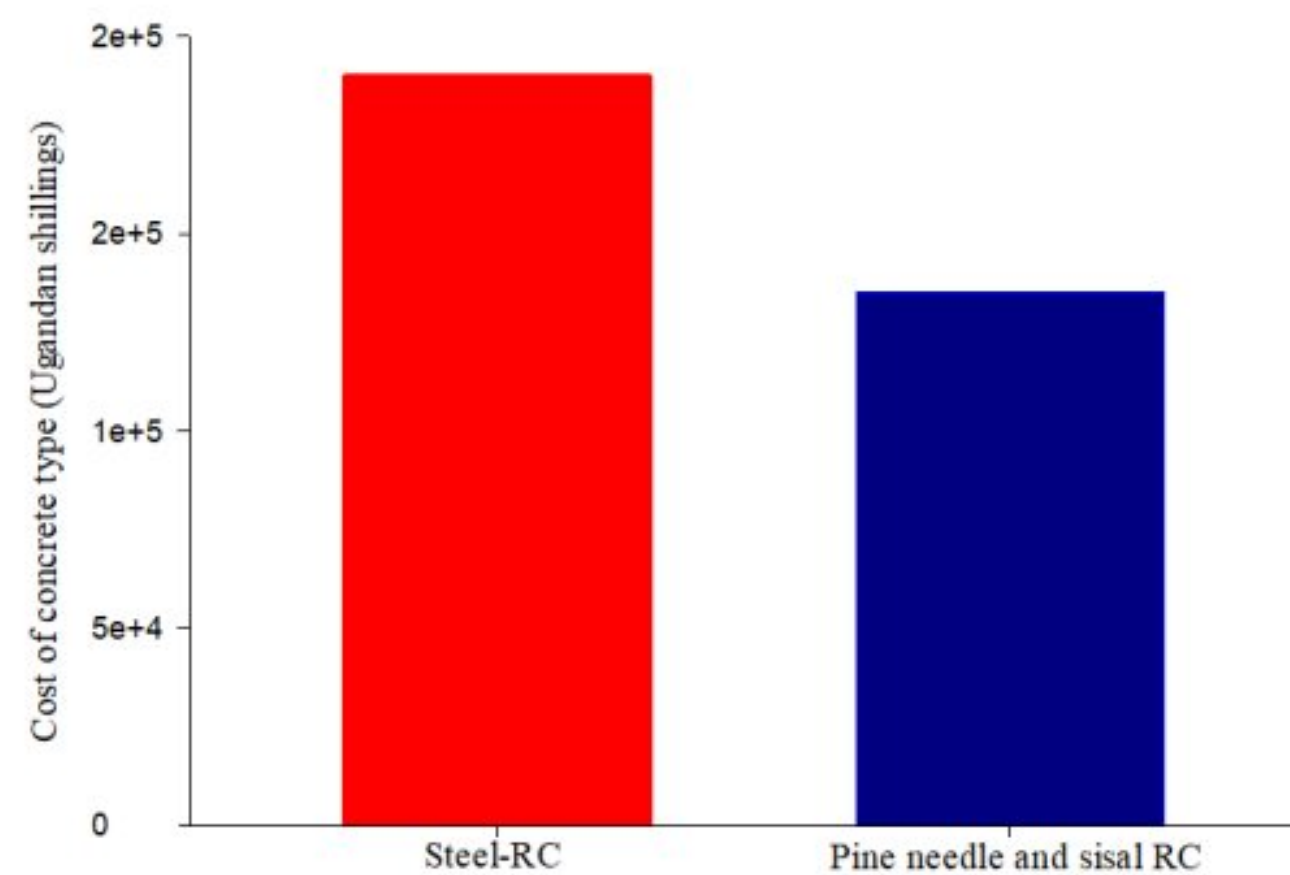
Sample	Concrete covers	Initial specimen observation	Final specimen observation
1. Plain concrete, 3-samples	15mm, 20mm, 30mm	The concrete specimens appeared normal with no visible cracks, the surface was smooth and the colour was uniform.	No significant visible degradation, or cracks, Slight surface discoloration, Increased surface roughness
2. 0.1%-Sisal fibre reinforced concrete, 3-samples	15mm, 20mm, 30mm		
3. 0.1%-Pine needle fibre reinforced concrete, 3-samples	15mm, 20mm, 30mm		
4. 0.1% and 0.1% sisal and pine needle fibre reinforced concrete, 3-samples	15mm, 20mm, 30mm		

These findings suggest that the composite materials have potential for use in structures exposed to alkaline environments, although further testing is necessary to fully understand their long-term durability.

4.5 Economic viability and environmental benefit analysis

A compressive analysis was conducted, evaluating economic aspects such as material costs, production expenses, and potential economic and environmental savings, considering environmental factors like reduction in carbon footprint, conserving resources, and minimizing environmental generated waste. through this investigation, the study aimed to put more light on the potential and cost, and environmental implications of adopting pine needle and sisal fibre reinforced concrete in comparison with steel reinforced concrete, ultimately triggering the contribution into the advanced-growth of eco-friendly construction solutions and reduced environmental impact.

A comparative cost benefit analysis (shown in [Figure 4.17](#)) of reinforcing a typical $0.3 \times 0.4 \times 3\text{m}$ span beam with traditional steel versus natural fibres (pine needle and sisal fibres). Notably, the natural fibre reinforcement achieved 21.7% improvement in tensile strength, prompting a calculation of equivalent steel reinforcement (T16mm diameter) to match this performance. A comprehensive cost comparison was then conducted, revealing a significant cost saving of Ugandan Shillings 55,000 when using natural fibres. The illustrates the cost comparison between the two reinforcement options, highlighting the economic benefits of using natural fibres.



[Figure 4.17](#) cost comparison between the NFRC and the steel RC

One of the critical objectives of this study was to understand the environmental impact when natural fibres are used in comparison with the traditional steel reinforced concrete. The analysis estimated that the application of steel reinforcement to improve the tensile strength of a $0.3 \times 0.4 \times 3\text{m}$ beam by an equivalence of 21.7% tensile strength improvement that was recorded in the use of fibres would result in approximately 34.4 kg of CO₂ emission. Considering factors such as transportation and generator use in the fibre processing, see [Figure 4.18](#)

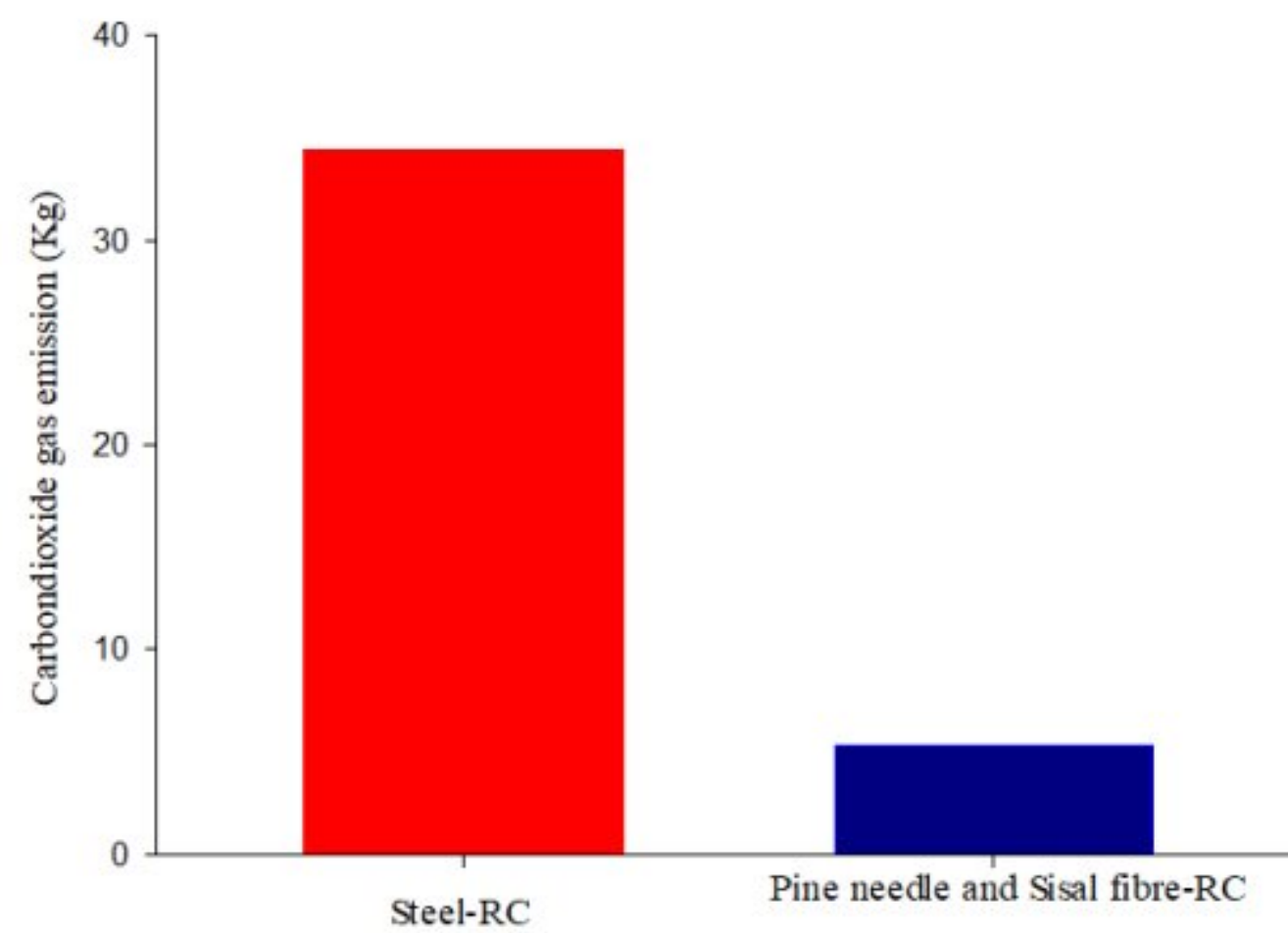


Figure 4.18 carbon dioxide gas emission comparison between NFRC and the steel RC

The use of natural pine needle and sisal fibres in concrete reinforcement reduces abiotic depletion by utilizing renewable, biodegradable waste materials, thereby minimizing the surrounding effect related to the extraction and the processes of material preparation required for steel production. The [Table 4.6](#) below elaborates the environmental impacts, benefits and possible applications of the pine needle and sisal fibre reinforced concrete composite.

Table 4.6 Environmental impact, benefits and applications

Material	Environmental impact	Potential benefits	Potential applications
Pine needle and sisal fibre reinforced concrete	Low	Reduced steel usage, Improved durability, Cost effective, environmentally sustainable. Highly renewable resources	Low-cost housing, Pre-cast concrete products, Sustainable infrastructure, Eco-friendly construction
Steel rebar concrete	High	High strength durability	High-rise buildings, complex structures, heavy infrastructure

The analysis suggest that the natural fibre composite material offers a promising balance of economic viability and environmental benefits as shown in table 8 above.

With its potential to reduce environmental impacts while maintaining competitive costs. Further research needed to optimise its performance and sustainability.

4.6 Summary

The study revealed that addition of pine needle and sisal fibres either as individual or hybrid fibres decreases the compressive characteristic strength of the concrete compared to the plain or neat concrete. The optimal content of pine needle and sisal fibres for improved strength properties of concrete is 0.1% (compressive strength) and 0.2% (tensile strength) by weight. Higher fibre content beyond 0.2% leads to significant reductions in concrete strength properties. The 0.1% and 0.2% fibre reinforced concrete samples meet the design target for class 20 N/mm². The water absorption test results indicate that addition of sisal fibres into concrete generally increases its water absorption up about 12.5% compared to plain concrete. The optimal fibre proportions were determined based on the maximum strength property achievement, particularly the compressive potential and also workability, which affects the concrete strength properties. All the samples showed resistance to the alkaline conditions, with minimal impact observed in the simulated an alkaline environment, suggesting an optimal minimum concrete cover of at least 20mm.

The findings reveal that adding sisal or pine needle fibres either as individual or hybrid fibres to concrete improves its tensile strength at least by 21.7%. The study also revealed a slight least reduction of 2.5% in flexural strength on addition of 0.1% pine needle fibres into concrete. The use of natural fibres (pine needle and sisal fibres) in concrete reinforcement resulted in cost saving of 55,000 Ugandan shillings compared to traditional steel reinforcement.

Natural fibre reinforcement yielded a significant reduction in CO₂ emission from 34.4 kg to 5.28 kg, contributing to environmental benefits. The utilization of renewable, biodegradable waste materials minimizes the environmental-surrounding impacts related with abiotic depletion and processing raw materials for steel production, promoting sustainability.

The variations in the strength impacts given by the two fibres are because of the differences in fibre mechanical and physical related attributes, for example the breaking elongation, tensile strength, diameter of fibres, Youngs modulus etc. Sisal fibres having unique properties for example breaking force greater than that of pine needle this could mean resistance to loading. Sisal fibre also has a small surface area to volume ration, at the same time with a rough texture, this allowed effectiveness in the character of bonding in between the concrete matrix and the fibre. On the other hand, the pine needle fibre has larger diameters, possibly allowing larger deformations. However, it has a smooth texture surface, possibly leading to inadequacy in bonding properties.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

This chapter consolidates the core outcomes of an experimental inquiry into the behaviour of concrete augmented with sisal and pine needle fibres. The study examined the interplay between fibre reinforcement and concrete strength properties, including flexural strength, compressive strength, split tensile strength, water absorption, corrosion resistance under alkaline environments. Drawing on the empirical evidence and predictive model validation, the conclusion and recommendations outlined herein aim to inform future research trajectories and practical applications, highly adding to the advancement of the eco-friendly and sustainable resilient concrete solutions.

5.2 Conclusions

Pine needle and sisal fibres demonstrate suitability as concrete ingredients demonstrating moderately good physical and mechanical properties i.e. breaking force, breaking elongation, diameter, tensile strength in reference to the ASTM D3822. Sisal fibres exhibit higher tensile strength (123.34 N/mm^2) and elastic modulus, making them more suitable for improving concrete strength properties. Pine needle fibres have larger diameters, with lower tensile strength (15.6 N/mm^2) and elastic modulus (0.716 GPa).

Optimal fibre-proportion of 0.1-0.2% by weight yields improved split tensile strength, but reduced compressive characteristic and flexural strength by 21.7% and 2.5% respectively. However, the target concrete strength of 20 N/mm^2 was achieved, notably a 0.1% sisal fibre contents exhibits superior compressive strength properties compared to pine needle fibre reinforced concrete.

There was increased water absorption recorded due to addition of fibres into the concrete, the pine needle and sisal FRC material exhibits resistance to alkaline environment, no fibre degradation was observed except the colour change.

The use of pine needle and sisal fibres in concrete reinforcement resulted in cost saving of 55,000 Ugandan shillings compared to traditional steel reinforcement based on a typical beam design of 0.3m×0.4m×3m, volume of 0.36m³. Notably, basing on the improved split tensile strength comparison made. Natural fibre reinforcement yielded a significant reduction in CO₂ emission from 34.4 kg to 5.28 kg, contributing to environmental benefits. The pine needle and sisal fibres show engineering viability for concrete applications, offering a sustainable solution.

5.3 Recommendations

5.3.1 Engineering practice and applications guidelines

- 1) Use optimal fibre content (0.1-0.2% by weight) for improved strength properties.
- 2) Consider both fibres for applications requiring enhanced concrete tensile strength.
- 3) Ensure minimum concrete cover of at least 20mm for short term durability.

5.3.2 Policy and environmental recommendations

- 1) Promote the applications of the natural-fibres in building and construction industry through incentives and regulations.
- 2) Develop standards for natural fibre reinforced concrete applications.

- 3) Encourage sustainable construction practices and waste reduction.

5.3.3 Recommendations for further research

- 1) Future research is critical to explore the effect of fibre length, orientation, and chemical treatment of pine needle and sisal fibres on the strength properties of concrete. Considering accessing fibres from upcountry since they are available.
- 2) Further research is recommended to assess the fire resistance and the structural performance of the pine needle and sisal fibre concrete composite material.
- 3) Further research is required to investigate the effect of pine needle and sisal fibre chemical treatment on the strength properties of the concrete.
- 4) Further research is recommended for the life cycle analysis for the pine needle and sisal fibre reinforced concrete composite.

5.3.4 Research limitations

The time constraints limited the scope of testing and analysis

Financial constraints restricted the number of samples and testing conducted

Inadequate laboratory equipment limited the research exploration.

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APPENDICES

APPENDIX A



Plate A.1: Pine needle fibres



Plate A.2: Pine needle tree where needles are harvested



Plate A.3: Sisal fibre plantation, where sisal fibres are harvested from



Plate A.4: Processed sisal fibres



Plate A.5: Sorting and sizing of sisal fibres



Plate A.6: Sorting and sizing of pine needle fibres



Plate A.7: A three point-flexural strength test



Plate A.8: Compressive strength test



Plate A.9: Casting of compressive strength samples



Plate A.10: Casting of split tensile strength samples



Plate A.11: Samples for split tensile strength test



Plate A.12: Observation of specimens and record taking

APPENDIX B: LABORATORY RESULTS



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TEST CERTIFICATE FOR AGGREGATES

CLIENT : M/S ONYANGO JULIUS

PROJECT: STENGTH PROPERTIES OF CONCRETE INCOPORATING PINE NEEDLE & SISAL FIBRE COMPOSITES

DATE : 03 JULY 2025

Test Standards and Methods: BS 882:1992, BS 812-103.1, BS EN 1097-2:2020 and MoWT: 2005

Material Source and Description: White Gray Black Granite Rock from a stockpile in Namanve

Sample Ref : CML:002/08/05/25

A. Grading & Shape 20mm Single Sized Aggregate

Sieve Size (mm)	Percentage Passing the BS Sieve (%)	Specification BS 882:1992 Concrete Works (%)
37.5	100	100
20.0	96	85-100
14.0	76	0-70
10.0	38	0-25
5.0	4	0-5
Flakiness Index (%)	27	35 Maximum

B. Physical and Mechanical Strength Tests

Property	Unit	Results	Specifications BS 882:1992 Concrete Works
Aggregate Impact Value (AIV)	%	9	25 maximum
Aggregate Crushing Value (ACV)	%	15	30 maximum
Los Angeles Abrasion Value (LAAB)	%	28	50 maximum
Ten Percent Fines Value (Dry) (TFV Dry)	kN	210	100 minimum
Sodium Sulphate Soundness (SSS)	%	0.2	12 maximum
Water Absorption (WA)	%	0.5	2 maximum
Specific Gravity (GS)	-	2.60	-


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TEST CERTIFICATE FOR SAND SAMPLE

CLIENT : M/S ONYANGO JULIUS
PROJECT : STRENGTH PROPERTIES OF CONCRETE INCORPORATING PINE NEEDLE & SISAL
DATE : 03 JULY 2025
Test Standards and Methods: BS 882:1992, BS 812-103.1, BS EN 933-8:2012 and AASHTO T21
Material Source and Description: Light Brown White Medium Sand from a stockpile in Namanve
Sample Ref : CML: 002/08/05/25

A. Grading

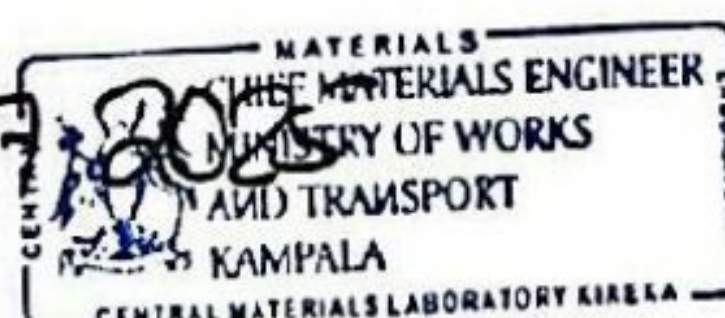
Sieve Size (mm)	Percentage Passing the BS Sieves (%)	Specifications BS 882:1992 (Concrete Works)	
		Overall Limits (%)	Additional Limits – M (%)
10.0	100	100	-
5.0	100	89-100	-
2.36	96	60-100	65 – 100
1.18	78	30-100	45 – 100
0.600	41	15-100	25 – 100
0.300	17	5-70	5 – 48
0.150	4	0-15	-
Fineness Modulus (FM)		2.65	

B. Other Parameters

Parameter	Result	Specifications BS 882:1992 (Concrete Works)
Silt Content (%)	2	4 Maximum
Sand Equivalent (%)	96	-
Organic matter Content by colour comparison (AASHTO Designation: 21:00)	Lighter than the Standard Reference colour	Lighter than the Standard reference colour*

Remarks: *Sand for mortar and concrete shall be free of injurious amounts of organic impurities whose presence is indicated by a colour darker than the standard reference colour, M-Medium.

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TEST CERTIFICATE FOR SAND SAMPLE

CLIENT : M/S ONYANGO JULIUS
 PROJECT : STRENGTH PROPERTIES OF CONCRETE INCORPORATING PINE NEEDLE AND SISAL
 DATE : FIBRE COMPOSITES
 : 03 JULY 2025

Test Standards and Methods : BS 882:1992, BS 812-103.1, BS EN 933-8:2012 and AASHTO T21
 Material Source and Description : Light Brown White medium sand from a stockpile in Namanve
 Sample Ref : CML:002/08/05/25

Evaluation of Fineness Modulus for Sand

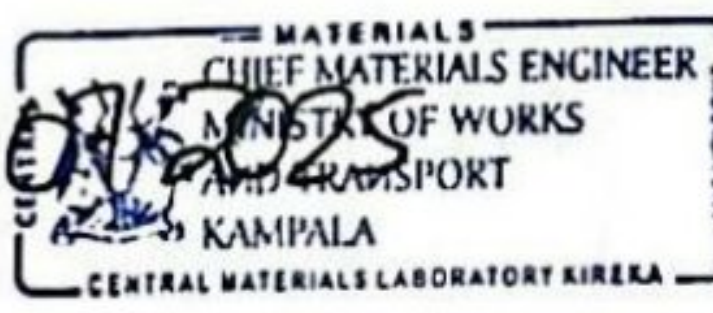
Sieve Size (mm)	Mass Retained (g)	% Mass Retained (%)	Cumulative % Retained (%)	Fineness Modulus (FM)
10	0	0	0	2.65
5.0	2	0.18	0.18	
2.36	47	4.23	4.41	
1.18	193	17.37	21.78	
0.600	409	36.81	58.59	
0.300	275	24.75	83.34	
0.150	143	12.87	96.21	
Total	1069	96.21	264.51	-

Fineness Modulus (FM) = $\frac{\text{Sum of Cumulative percentage retained}}{100}$

$$FM = \frac{264.51}{100} = 2.65$$

For: Fine Sand FM 2.2 – 2.6
 Medium Sand FM 2.6 – 2.9
 Coarse sand FM 2.9 – 3.2


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TEST CERTIFICATE FOR CONCRETE MIX DESIGN

CLIENT : MR ONYANGO JULIUS
PROJECT : COMPRESSIVE STRENGTH OF CONCRETE INCORPORATING PINE NEEDLE AND SISAL FIBRE COMPOSITES

DATE : 03 JULY 2025

SAMPLE REF: CML:002/08/05/25

MIX DESIGN PROPORTIONS FOR CLASS C20- DOE- Concrete mix design

Class of concrete	Type of cement	Cement content (kg/m ³)	Sand content (kg/m ³)	Coarse Aggregates (kg/m ³)	Pine Needle content (%)	Water content (kg/m ³)	Measured slump (mm)
C20	Tororo Portland Cement CEM II/32.5N	377	822	891	0	230	55
		377	822	891	0.1	230	55
		377	822	891	0.2	230	53
		377	822	891	0.5	230	49
		377	822	891	1.5	230	45
		377	822	891	2.0	230	40

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TEST CERTIFICATE FOR CONCRETE MIX DESIGN

CLIENT : MR ONYANGO JULIUS
PROJECT : COMPRESSIVE STRENGTH OF CONCRETE INCORPORATING PINE NEEDLE AND SISAL FIBRE COMPOSITES
DATE : 03 JULY 2025
SAMPLE REF.: CML:002/08/05/25

MIX DESIGN PROPORTIONS FOR CLASS C20- DOE- Concrete mix design

Class of concrete	Type of cement	Cement content (kg/m ³)	Sand content (kg/m ³)	Coarse Aggregates (kg/m ³)	Sisal fibre content (%)	Water content (kg/m ³)	Measured slump (mm)
C20	Tororo Portland Cement CEM II/32.5N	377	822	891	0	230	55
		377	822	891	0.1	230	54
		377	822	891	0.2	230	51
		377	822	891	0.5	230	47
		377	822	891	1.5	230	41
		377	822	891	2.0	230	33

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TEST CERTIFICATE FOR MECHANICAL PROPERTIES OF CONCRETE CYLINDERS

CLIENT : M/S ONYANGO JULIUS
UNIVERSITY : KYAMBOGO UNIVERSITY, FACULTY OF ENGINEERING
PROJECT : STRENGTH PROPERTIES OF CONCRETE INCORPORATING PINE NEEDLE AND SISAL FIBRE COMPOSITES
Date : 03 JULY 2025

Test Standard: BS EN 12390-3: 2019, (Part 3: Compressive strength of test specimens)
Sample Ref.: CML: 002/08/05/25
Sample Age : 07 Days

A. Uniaxial Compressive Test (UCS)

SNo.	Sample Label	Sample Identification	Sample Weight (Kg)	Specimen Diameter (mm)	Length (mm)	Max. Splitting Force (kN)	Uniaxial Comp. Strength (MPa)	Water Absorption (%)
1.	Neat	Sample 1	4251	100	197	74.50	2.41	8.2
2.		Sample 2	4316	100	200	65.40	2.08	
3.		Sample 3	4344	100	210	70.55	2.14	
4.	Sisal Fiber 0.5%	Sample 1	4142	100	200	65.10	2.07	12.4
5.		Sample 2	4046	100	195	66.20	2.16	
6.		Sample 3	3983	100	195	65.10	2.13	
7.	Sisal Fiber 1.5%	Sample 1	3948	100	210	50.05	1.52	10.5
8.		Sample 2	3664	100	200	50.05	1.59	
9.		Sample 3	3904	100	200	50.10	1.59	
10.	Sisal Fiber 2.0%	Sample 1	3831	100	200	7.90	0.25	9.5
11.		Sample 2	3764	100	210	3.35	0.10	
12.		Sample 3	3470	100	210	11.05	0.33	
13.	Pine Needle 0.5%	Sample 1	4343	100	200	53.05	1.69	9.0
14.		Sample 2	4332	100	210	52.80	1.60	
15.		Sample 3	4267	100	200	53.95	1.72	

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CLIENT : M/S ONYANGO JULIUS
PROJECT : STRENGTH PROPERTIES OF CONCRETE INCORPORATING PINE NEEDLE AND SISAL FIBRE COMPOSITES
DATE : 03 JULY 2025
Test standards and methods : BS EN 12390-3:2019, (Part 3: Compressive strength of specimens)
Sample ref: : CML:002/08/05/25
Test Age : 28 days

Date made/label	Date tested	Dimensions (mm)	Weight (Kg)	Density (kg/m ³)	Crushing load (kN)	Ultimate comp. Strength (Mpa)
12.03.2025	09.04.2025	150x150x150	8.2	2430	713	31.7
Neat	.	.	8.1	2400	786	35.0
C20	.	.	8.2	2430	750	33.3

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PROJECT : STRENGTH PROPERTIES OF CONCRETE INCORPORATING PINE NEEDLE AND SISAL FIBRE COMPOSITES
DATE : 03 JULY 2025
Test standards and methods : BS EN 12390-3:2019, (Part 3: Compressive strength of specimens)
Sample ref: : CML:002/08/05/25
Test Age : 7 days

Date made/label	Date tested	Dimensions (mm)	Weight (Kg)	Density (kg/m ³)	Crushing load (kN)	Ultimate comp. Strength (Mpa)
12.03.2025 Neat C20	19.03.2025 "	150x150x150 "	8.3 8.1 8.0	2459 2400 2370	525 575 529	23.3 25.5 23.5
03.04.2025 0.2% pine needle & 0.2% sisal C20	10.04.2025 "	150x150x150 "	7.9 7.9 7.9	2341 2341 2341	336 325 342	14.9 14.4 15.2


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Test standards and methods : BS EN 12390-3:2019, (Part 3: Compressive strength of specimens)
Sample ref: : CML:002/08/05/25
Test Age : 7 days

Date made/label	Date tested	Dimensions (mm)	Weight (Kg)	Density (kg/m ³)	Crushing load (kN)	Ultimate comp. Strength (Mpa)
03.04.2025 0.1% pine needle C20	10.04.2025 *	150x150x150 *	8.2 8.1 8.1	2430 2400 2400	412 437 415	18.3 19.4 18.4
03.04.2025 0.2% pine needle C20	10.04.2025 *	150x150x150 *	8.1 8.2 8.1	2400 2430 2400	410 427 381	18.2 18.9 17.0

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DATE : 03 JULY 2025
Test standards and methods : BS EN 12390-3:2019, (Part 3: Compressive strength of specimens)
Sample ref: : CML:002/08/05/25
Test Age : 7 days

Date made/label	Date tested	Dimensions (mm)	Weight (Kg)	Density (kg/m ³)	Crushing load (kN)	Ultimate comp. Strength (Mpa)
03.04.2025 0.1% sisal C20	10.04.2025 "	150x150x150 "	8.0 8.1 8.0	2370 2400 2370	388 399 407	17.2 17.7 18.1
03.04.2025 0.2% sisal C20	10.04.2025 "	150x150x150 "	8.0 8.1 8.0	2370 2400 2370	398 371 413	17.7 16.5 18.4

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Sample ref: : CML:002/08/05/25
Test Age : 7 days

Date made/label	Date tested	Dimensions (mm)	Weight (kg)	Density (kg/m ³)	Crushing load (kN)	Ultimate comp. Strength (Mpa)
17.03.2025	24.03.2025	150x150x150	7.5	2222	15	0.7
2% pine needle	"	"	7.5	2222	16	0.7
	"	"	7.4	2193	15	0.7
14.03.2025	21.03.2025	150x150x150	8.1	2400	306	13.6
0.5% pine needle	"	"	8.0	2370	279	12.4
	"	"	8.0	2370	283	12.6
14.03.2025	21.03.2025	150x150x150	7.7	2281	43	1.9
1.5% pine needle	"	"	7.7	2281	41	1.8
	"	"	7.8	2311	49	2.2

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 PROJECT : STRENGTH PROPERTIES OF CONCRETE INCORPORATING PINE NEEDLE AND SISAL FIBRE COMPOSITES
 DATE : 03 JULY 2025
 Test standards and methods : BS EN 12390-3:2019, (Part 3: Compressive strength of specimens)
 Sample ref: : CML:002/08/05/25
 Test Age : 7 days

Date made/label	Date tested	Dimensions (mm)	Weight (Kg)	Density (kg/m ³)	Crushing load (kN)	Ultimate comp. strength (Mpa)
12.03.2025 0.5% sisal fibre C20	19.03.2025 "	150x150x150 "	8.0 8.0 8.0	2370 2370 2370	398 378 363	17.7 16.8 16.1
14.03.2025 1.5% sisal fibre C20	21.03.2025 "	150x150x150 "	7.2 7.2 7.3	2133 2133 2163	115 113 122	5.1 5.0 5.4
14.03.2025 2% sisal fibre C20	21.03.2025 "	150x150x150 "	7.1 7.0 7.0	2104 2074 2074	98 87 70	4.4 3.9 3.1

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CLIENT : M/S ONYANGO JULIUS
PROJECT : STRENGTH PROPERTIES OF CONCRETE INCORPORATING PINE NEEDLE AND SISAL FIBRE COMPOSITES
DATE : 03 JULY 2025
Test standards and methods : BS EN 12390-3:2019, (Part 3: Compressive strength of specimens)
Sample ref: : CML:002/08/05/25
Test Age : 7 days

Date made/label	Date tested	Dimensions (mm)	Weight (Kg)	Density (kg/m ³)	Crushing load (kN)	Ultimate comp. Strength (Mpa)
17.03.2025 0.5% each sisal & pine C20	24.03.2025 -	150x150x150 -	7.9 8.0 8.0	2341 2370 2370	322 327 294	14.3 14.5 13.1
17.03.2025 1.0% sisal & 0.5% pine C20	24.03.2025 -	150x150x150 -	7.1 7.4 7.3	2104 2193 2163	17 18 18	0.8 0.8 0.8
17.03.2025 1% pine & 0.5% sisal C20	24.03.2025 -	150x150x150 -	7.5 7.4 7.5	2222 2193 2222	48 49 49	2.1 2.2 2.2

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DATE : 03 JULY 2025
Test standards and methods : BS EN 12390-3:2019, (Part 3: Compressive strength of specimens)
Sample ref: : CML-002/08/05/25
Test Age : 7 days

Date made/label	Date tested	Dimensions (mm)	Weight (Kg)	Density (kg/m ³)	Crushing load (kN)	Ultimate comp. Strength (Mpa)
12.03.2025 0.5% sisal fibre C20	19.03.2025 "	150x150x150 "	8.0 8.0 8.0	2370 2370 2370	398 378 363	17.7 16.8 16.1
14.03.2025 1.5% sisal fibre C20	21.03.2025 "	150x150x150 "	7.2 7.2 7.3	2133 2133 2163	115 113 122	5.1 5.0 5.4
14.03.2025 2% sisal fibre C20	21.03.2025 "	150x150x150 "	7.1 7.0 7.0	2104 2074 2074	98 87 70	4.4 3.9 3.1

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DATE : 03 JULY 2025
Test standards and methods : BS EN 12390-3:2019, (Part 3: Compressive strength of specimens)
Sample ref: : CML:002/08/05/25
Test Age : 7 days

Date made/label	Date tested	Dimensions (mm)	Weight (Kg)	Density (kg/m ³)	Crushing load (kN)	Ultimate comp. Strength (Mpa)
17.03.2025 0.5% each sisal & pine C20	24.03.2025 "	150x150x150 "	7.9 8.0 8.0	2341 2370 2370	322 327 294	14.3 14.5 13.1
17.03.2025 1.0% sisal & 0.5% pine C20	24.03.2025 "	150x150x150 "	7.1 7.4 7.3	2104 2193 2163	17 18 18	0.8 0.8 0.8
17.03.2025 1% pine & 0.5% sisal C20	24.03.2025 "	150x150x150 "	7.5 7.4 7.5	2222 2193 2222	48 49 49	2.1 2.2 2.2

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CENTRAL MATERIALS LABORATORY KIREKA



MINISTRY OF WORKS AND TRANSPORT
MATERIALS TESTING AND RESEARCH DIVISION
CENTRAL MATERIALS LABORATORY- KIREKA
P.O. Box 7174, Kampala-Uganda. Tel: 256-414-287132, Email: cmli@works.gov.ug
TEST CERTIFICATE FOR CONCRETE CUBES

CLIENT : M/S ONYANGO JULIUS
PROJECT : STRENGTH PROPERTIES OF CONCRETE INCORPORATING PINE NEEDLE AND SISAL FIBRE COMPOSITES
DATE : 03 JULY 2025
Test standards and methods : BS EN 12390-3:2019, (Part 3: Compressive strength of specimens)
Sample ref: : CML:002/08/05/25
Test Age : 28 days

Date made/label	Date tested	Dimensions (mm)	Weight (kg)	Density (kg/m ³)	Crushing load (kN)	Ultimate comp. Strength (Mpa)
17.03.2025 2% pine needle	14.04.2025 *	150x150x150 *	7.2 7.5 7.5	2133 2222 2222	29 34 27	1.3 1.5 1.2
14.03.2025 0.5% pine needle	11.04.2025 *	150x150x150 *	8.0 8.0 8.0	2370 2370 2370	445 481 483	19.8 21.4 21.5
14.03.2025 1.5% pine needle	11.04.2025 *	150x150x150 *	7.8 7.8 7.8	2311 2311 2311	129 140 112	5.7 6.2 5.0

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Sample ref: : CML-002/08/05/25
Test Age : 28 days

Date made/label	Date tested	Dimensions (mm)	Weight (Kg)	Density (kg/m ³)	Crushing load (kN)	Ultimate comp. Strength (Mpa)
12.03.2025 0.5% sisal C20	09.04.2025 .	150x150x150 .	7.9 8.0 7.9	2341 2370 2341	491 575 536	21.8 25.6 23.8
12.03.2025 1.5% sisal C20	09.04.2025 .	150x150x150 .	7.4 7.2 7.2	2193 2133 2133	222 198 221	9.9 8.8 9.8
12.03.2025 2% sisal C20	09.04.2025 .	150x150x150 .	6.9 6.9 7.1	2044 2044 2104	141 135 152	6.3 6.0 6.8

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DATE : 03 JULY 2025
Test standards and methods : BS EN 12390-3:2019, (Part 3: Compressive strength of specimens)
Sample ref: : CML:002/08/05/25
Test Age : 28 days

Date made/label	Date tested	Dimensions (mm)	Weight (Kg)	Density (kg/m ³)	Crushing load (kN)	Ultimate comp. Strength (Mpa)
17.03.2025 0.5% each sisal & pine C20	14.04.2025	150x150x150	7.9 8.0 8.0	2341 2370 2370	488 519 479	21.7 23.1 21.3
17.03.2025 1% pine & 0.5% sisal C20	14.04.2025	150x150x150	7.5 7.6 7.5	2222 2252 2222	158 201 172	7.0 8.9 7.7
17.03.2025 1% sisal & 0.5% pine C20	14.04.2025	150x150x150	7.2 7.3 7.2	2133 2163 2133	47 43 37	2.1 1.9 1.7

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TEST CERTIFICATE FOR MECHANICAL PROPERTIES OF CONCRETE CYLINDERS

CLIENT : M/S ONYANGO JULIUS
 UNIVERSITY : KYAMBOGO UNIVERSITY, FACULTY OF ENGINEERING
 PROJECT : STRENGTH PROPERTIES OF CONCRETE INCORPORATING PINE NEEDLE AND
 SISAL FIBRE COMPOSITES
 Date : 03 JULY 2025

Test Standard: BS EN 12390-3: 2019, (Part 3: Compressive strength of test specimens)
 Sample Ref.: CML: 002/08/05/25
 Sample Age : 07 Days

A. Uniaxial Compressive Test (UCS)

SNo.	Sample Label	Sample Identification	Sample Weight (Kg)	Specimen Diameter (mm)	Length (mm)	Max. Splitting Force (kN)	Uniaxial Comp. Strength (MPa)	Water Absorption (%)
1.	Neat	Sample 1	4251	100	197	74.50	2.41	8.2
2.		Sample 2	4316	100	200	65.40	2.08	
3.		Sample 3	4344	100	210	70.55	2.14	
4.	Sisal Fiber 0.5%	Sample 1	4142	100	200	65.10	2.07	12.4
5.		Sample 2	4046	100	195	66.20	2.16	
6.		Sample 3	3983	100	195	65.10	2.13	
7.	Sisal Fiber 1.5%	Sample 1	3948	100	210	50.05	1.52	10.5
8.		Sample 2	3664	100	200	50.05	1.59	
9.		Sample 3	3904	100	200	50.10	1.59	
10.	Sisal Fiber 2.0%	Sample 1	3831	100	200	7.90	0.25	9.5
11.		Sample 2	3764	100	210	3.35	0.10	
12.		Sample 3	3470	100	210	11.05	0.33	
13.	Pine Needle 0.5%	Sample 1	4343	100	200	53.05	1.69	9.0
14.		Sample 2	4332	100	210	52.80	1.60	
15.		Sample 3	4267	100	200	53.95	1.72	

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CLIENT : M/S ONYANGO JULIUS
 UNIVERSITY : KYAMBOGO UNIVERSITY, FACULTY OF ENGINEERING
 PROJECT : STRENGTH PROPERTIES OF CONCRETE INCORPORATING PINE NEEDLE AND
 SISAL FIBRE COMPOSITES
 DATE : 03 JULY 2025
 Test Standard: BS EN 12390-3: 2019, (Part 3: Compressive strength of test specimens)
 Sample Ref. : CML: 002/08/05/25
 Sample Age : 07 Days

A. Uniaxial Compressive Test (UCS)

SNo.	Sample Label	Sample Identification	Sample Weight (Kg)	Specimen Diameter (mm)	Length (mm)	Max. Splitting Force (kN)	Uniaxial Comp. Strength (MPa)	Water Absorption (%)
16.	Pine Needle 1.5%	Sample 1	4099	100	210	14.95	0.45	8.2
17.		Sample 2	3966	100	200	14.90	0.47	
18.		Sample 3	3958	100	200	14.45	0.46	
19.	Pine Needle 2.0%	Sample 1	4159	100	210	14.70	0.45	12.4
20.		Sample 2	4362	100	210	14.05	0.43	
21.		Sample 3	4224	100	210	13.10	0.40	
22.	Composite 0.5% Each	Sample 1	4118	100	200	27.40	0.87	10.5
23.		Sample 2	4051	100	200	28.60	0.91	
24.		Sample 3	4144	100	210	27.65	0.84	

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FACULTY OF ENGINEERING AND TECHNOLOGY
DEPARTMENT OF POLYMER, TEXTILE & INDUSTRIAL ENGINEERING
Section of Materials, Metallurgy and Textile Laboratory

Thursday 6th March, 2025

Mr. Onyango,
Kyambogo University.

RE: TEST RESULTS FOR SISAL AND PINE FIBRES

Table 1: Physical and Mechanical Properties of sisal and pine fibres

S/n	Fibre parameter	Equipment/Requirement	Test result	
			Sisal	Pine
1.	Diameter (μm)	Scanning Electron Microscope (TESCAN VEGA 3 SEM)	0.23	0.51
2.	Breaking force (cN)	YG003E Single fibre strength tester	512.47	318.68
3.	Breaking elongation (%)	YG003E Single fibre strength tester	5.43	2.18
4.	Tensile strength (MPa)	Breaking force and diameter	123.34	15.6
5.	Elastic modulus (GPa)	Tensile strength and elongation	2.27	0.716

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