CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY, ISLAMABAD

Development of Bendable Composite Using Local Materials and Its Potential for Structural Elements

by

Amaan Sikandar

A thesis submitted in partial fulfillment for the degree of Master of Science

in the

Faculty of Engineering
Department of Civil Engineering

2023

This effort is dedicated with heartfelt gratitude and love to my beloved parents, whose unwavering support and boundless love have been my guiding light throughout this journey. To my cherished wife, whose patience, encouragement, and understanding have been my greatest blessings. And to my respected supervisor, whose wisdom and guidance have shaped my path to knowledge and growth.

CERTIFICATE OF APPROVAL

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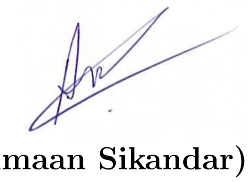
Journal Article

A. Sikandar and M. Ali. (2023). Exploring Potential of local materials for manufacturing of bendable composite in developing countries. Sustainable Materials and Technologies, (Impact Factor = 9.6, HEC, W-Gold Category, **Submitted**).

Conference Proceedings

1. **A. Sikandar and M. Ali**, "A Review on Different Materials Composition of Engineered Cementious Composites, Micromechanics and Structural Applications." *International Congress on Phenomenological Aspects in Civil Engineering, Istanbul,Turkey*, vol. 1, pp. 265-271, 2023.

2. **A. Sikabdar and M. Ali**, "Exploring Mechanical Properties of Engineered Cementitious Composite with Local Materials in Developing Countries." *The 1st International Online Conference on Buildings Advances in Building Planning, Design, Construction, and Operation, MDPI, Basel, Switzerland*, October 24-26, **Paper Submitted**.



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Acknowledgement

In the Name of Allah, The Most Gracious, The Most Merciful. Praise be to God, the Cherisher and Sustainer of the worlds. All thanks to Almighty Allah, The Lord of all that exist, who bestowed me with His greatest blessing i.e. knowledge and Wisdom to accomplish my task successfully. Thousands of salutations and benedictions to the Holy Prophet Hazrat Muhammad (PBUH) the chosen- through by whom grace the sacred Quran was descended from the Most High. I am very thankful to Engr. Prof. Dr. Majid Ali, a great teacher, supervisor and trainer who made a difference in all aspects of my life. I am indebted to Engr. Prof. Dr. Majid Ali for his valuable guidance, encouragement and dedicated support that enabled me to complete my MS Degree Program. I want to express my heartiest regards to my parents, my wife specially.

(Amaan Sikandar)

Abstract

In contemporary construction, sustainability is crucial, but traditional cement-based concrete faces challenges like low tensile strength and limited ductility. While concrete is essential in civil engineering for its mechanical properties, it's vulnerable to fractures and environmental factors. Enhancing it with synthetic and polymer fibers in precise proportions can greatly enhance its ductility and durability. Engineered Cementitious Composites (ECC), also known as bendable composites (BC), are fiber-reinforced materials with distinctive properties, including strain hardening and multiple fracture development. ECC exhibits impressive strain capacity and low fracture widths under tension, enhancing structural ductility and resilience. These fiber-reinforced cementitious composites, like ECC, are widely used to mitigate crack propagation and reduce brittle failures in traditional cement-based materials. The project aim involves creating an engineered cementitious composite with locally sourced materials, focusing on mechanical, dynamic, shrinkage, water absorption, and mass loss properties compared to standard cement composites. The study conducts experimental trials with varying fiber content percentages while ensuring material consistency. Micro-scale SEM testing reveals improved load-bearing capacity with polymer fiber integration in concrete. To reduce costs, the research explores locally available, cost-effective polymer fibers for flexible composite production, considering the high cost of PVA fibers.

To produce a bendable composite comprising fiberglass and polypropylene fibers, both fibers length are kept 6mm. The percentage of fiberglass and polypropylene fibers combine is adjusted at 1%, 1.5%, and 2% by volume. In addition to these fibers, fly ash is incorporated into the mixture as SCM. The superplasticizer is added at a dosage of 1.5% by weight of the binder. Ordinary Portland Cement and local sand are also essential components of the composite. Two different water-to-cement ratios are utilized: 0.45 for the PC Composite and 0.30 for the Bendable Composite. The mixing process initiates with the dry blending of cement, fly ash, and sand for 1 minute, followed by the addition of water and superplasticizer, with continued mixing for 3 minutes. The fibers are introduced at the end to ensure even dispersion, and mixing is carried out at high speed for 5 minutes. Slump test was conducted for fresh properties. After preparation, the samples are cured for 28 days before undergoing testing for mechanical, dynamic, and absorption properties.

2% PPGF-ECC has 87% higher water absorption than PC, while 1% and 1.5% PPGF-ECC also show increased rates (40% and 67%) compared to PC (46% less than 2% PPGF-ECC). PPGF-ECC displayed significant improvements in mechanical properties when compared to traditional plain concrete (PC). These improvements included enhanced strength, greater energy absorption both before and after reaching the peak, and a higher toughness index, showcasing the superior performance of PPGF-ECC. The hybrid fibers' bridging effect in the concrete effectively averted abrupt failures, leading to the retention of post-crack energy in all PPGF-ECC samples, unlike in PC. The inclusion of hybrid synthetic fibers enhances dynamic load resistance, resulting in improved damping ratio (Rd) and dynamic modulus (Ed) in PPGF-ECC cylinders and beamlets. SEM analysis of tested samples shows intact bonding between synthetic hybrid fibers and concrete, with G fibers exhibiting pull-out and PP fibers displaying breakage, including evidence of fiber bridging in fractured samples. This study highlights 1% PPGF-ECC (0.5%PP-0.5%G) and 2% PPGF-ECC (1%PP-1%G) as superior composites, recommended for countering spalling, cracking, flexural stress, and dynamic loads, especially in rigid pavements. Synthetic fibers offer a practical and sustainable construction material solution.

Key Words: Concrete, Bendable Composite, Engineered Cementitious Composite, Polypropylene Fibres, Glass Fibres, Pseudo Ductile, Durable, Structural Application, Sustainable Construction Material.

Contents

List of Figures

List of Tables

Abbreviations

1% PPGF-ECC	1% Polypropylene and Glass Fiber ECC
1.5% PPGF-ECC	1.5% Polypropylene and Glass Fiber ECC
2% PPGF-ECC	2% Polypropylene and Glass Fiber ECC
BC	Bendable Composite
CE1	Compressive Energy Before Failure
CE2	Compressive Energy After failure
CS	Compressive Strength
CTE	Compressive Total Energy
CTI	Compressive Toughness Energy
ECC	Engineered Cementitious Composite
FE1	Flexural Energy Before Failure
FE2	Flexural Energy After Failure
FRC	Fiber Reinforced Concrete
FS	Flexural Strength
FTE	Flexural Total Energy
FTI	Flexural Toughness Index
G	Glass Fiber
GPa	Giga Pascal
KN	Kilo-Newtons
ML	Mass-Loss
mm	Milimeter
MOE	Modulus of Elasticity
MOR	Modulus of Rupture

MPa	Mega Pascal
OPC	Ordinary-Portland Cement
PCC	Portland Cement Concrete
PP	Polypropylene Fiber
RC	Reinforced Concrete
RD	Modulus of Rigidity
RFL	Longitudnal Resonance Frequancy
RFR	Rotational Resonance Frequancy
RFT	Transverse Resonance Frequancy
SEM	Scaning Electron Microscopy
SP	Super-Plasticizers
WA	Water Absorption
W/C	Water Cement Ratio

Symbols

σ_o	Maximium Fiber Bridging Stress
ζ	Damping Ratio
σ_c	Matrix first-crack strength
(J_{tip})	Fracture tip toughness
$(J_b`)$	Fibre bridging complementary energy
δo	Deformation

Chapter 1

Introduction

1.1 Background

Concrete made of cement has a low tensile strength, weak ductility, and a high compressive strength. Concrete can be enhanced with specific ratios of synthetic and polymer fibers to improve its crucial ductility properties [1]. Engineered Cementitious Composite (ECC), a type of fiber-reinforced material, exhibits strain-hardening behavior and the development of multiple fractures. With meticulous micromechanics-based design, ECC can achieve a strain capacity of 3% and maintain fracture widths under 100 micrometers under tension stress, imparting remarkable ductility and strength to structures [1]. Due to its exceptional strain-hardening characteristics and superior mechanical performance, fiber-reinforced cementitious composites are commonly employed to mitigate crack propagation and reduce brittleness in traditional cement-based materials [2]. ECC, falling under this category, possesses high tensile strength and resilience, forming numerous fine fractures with widths less than 100 micrometers rather than one large crack. ECC can self-heal these small cracks when exposed to water and air [3, 4]. When subjected to tensile and bending loads, typical ECC exhibits robust energy dissipation capabilities and generates a significant number of fine fractures [5]. ECC, as a specialized class of fiber-reinforced cementitious composites, has been developed to enhance the impact resistance of structural materials [6]. The variety and width of cracks, which distinguish different ECC cracking behaviors, are closely linked to ECC's enhanced flexibility and durability[7]. In large-scale applications, ECC often utilizes locally sourced materials for economic and ecological reasons. In countries like Germany and Brazil, ECCs have been produced using regional raw materials and PVA fibers. China has also explored ECCs made with local PVA fibers. However, challenges remain in terms of mechanical properties and cost-effectiveness. Therefore, there is a need to explore alternative fiber options. Several attempts have been made to substitute some or all of the expensive PVA fibers with more affordable synthetic fibers such as polyethylene (PE), polypropylene (PP), and polycrylonitrile (PAN) fibers. Finding viable fiber alternatives is crucial, as the widespread adoption of ECC has been hindered by the high cost of PVA fibers [8]. When making a selection, it is important to take into account both the expense of ECC and the characteristics of the material. Construction materials are widely used in practical applications because of their balance between performance and cost. It is common knowledge that one of the main factors limiting the use of ECC is its high unit cost. Approximately 2% of PVA or PE fibres by volume are introduced to traditional ECC to ensure its ductility, and PVA costs make up 80% of the overall price of ECC material [8]. The PVA or PE fibres that were often used in ECC are substantially more expensive than steel fibres. According to Wang et al [9]. using PP fibres in place of PVA can lower the cost of fibres. In order to strengthen cement-based materials, this experimental investigation intends to create a ductile composite in which glass fibre and PP fibre are used. Commercial fibre glass and poly propylene fibre strands with a tiny diameter will be trimmed and chosen specifically for this use. The interfacial bonding characteristics of glass fibre, PP fibre, and cementitious matrix will next be assessed using three point bend testing of a single composite specimen and compared to PC. After that, the morphology of the glass fibre, PP fibre, and cementious matrix around the fibre will be characterized using sophisticated materials characterization methods including SEM. In order to explore and contrast the mechanical characteristics of the fibre reinforced cementitious composites employing glass fibres and PP fibres, three-point bending tests and compressive tests have been conducted.

1.2 Research Motivation and Problem Statement

In this modern era, sustainability is a necessity in construction. Concrete is a fundamental construction material in modern civil engineering, notably in structural, transportation and water resources infrastructure. Its popularity stems from its robust mechanical properties, ease of construction, and cost-effectiveness [10]. However, as an inorganic composite material, concrete possesses hydrophilic and porous characteristics. Without reinforcement, it is vulnerable to fracture under tensile and bending loads, creating pathways for aggressive ions when exposed to water, air, and temperature fluctuations. This accelerated deterioration significantly affects the mechanical properties and longevity of concrete structures, ultimately impacting their safety and operational lifespan [11]. Concrete consists of cement as main constituent, which exhibits CO2 emissions that is harmful for living beings. Therefore, supplementary cementitious material can be used to enhance toughness and strength of a composite [12]. Moreover textile products wastes i.e polymer fibers are residues left after being used, these material in the form of fibers can be used as reinforcement in concrete to enhance its tensile strength and make concrete resilient with pseudo ductile failure pattern [13]. Ductile failure of concrete is helpful indicating early warning of structural damage for evacuation of occupants or users of any structure. Studies are needed to focus on minimizing CO2 emissions for executing construction that is eco-friendly and also to enhance the mechanical properties of concrete for long life and sustainable application in structures. The problem statement is as following:

"Concrete is widely being used in construction but it has certain flaws like brittleness, weakness in tension and shrinkage cracks formation. Concrete exhibits brittle failure mechanism under load due to low tensile strength. According to literature

tensile strength of concrete is increased by introducing bendable composite phenomena, in which synthetic polymer (PVA) fibers having high tensile strength are added to reinforce concrete. It is reported that such phenomena not only makes concrete ductile but also produce eco-friendly concrete. Therefore it is important to develop bendable composite with local material having high tensile strength available, assess its potential for structural elements sustainable performance."

1.2.1 Research Questions

• What is the effect of glass fiber and polypropylene fiber on the tensile strength and strain of composite?
• What is the effect of glass fiber and polypropylene fiber on composite at the micro structure level?
• How sustainable will it be to use composite, having glass fiber and Polypropylene fiber, for structural application?
• To investigate the applications of the ECCs.?

1.3 Overall Objective of the Research Program and Specific Aim of this MS Thesis

The overall goal of the research program is to develop bendable composite ECC from local available textile polymer fiber material that exhibits good structure functioning as compared to conventional concrete and assess its potential for different civil engineering structural applications. Utilization of industrial waste fibers for production of eco-friendly composite that ensure sustainability in civil engineering. *"The Specific aim of this MS research thesis is to study the development of bendable composite ECC with local available materials and its beneficial behavior for making composite failure pattern pseudo ductile with its potential to be used in different structure elements in civil engineering applications."*

1.4 Scope of Work and Study Limitations

Scope of work consists of the production of engineered cementitious composite with the incorporation of available local materials. The material consists local cement, fine aggregate, Fly ash (class f), polymer fibres, superplasticizer and water for producing ECC. After production the mechanical properties i,e compressive strength, flexural strength and split tensile strength will be studied in comparison to plain cement composite [8]. Also the Dynamic modulus of rigidity, damping ratios, longitudinal frequency, transverse frequency and torsional frequency will be investigated. More over linear shrinkage, water absorption test of the specimen is carried. SEM test are also included in the scope of work. The study is limited to comparison of composite mechanical properties and other properties mentioned with plain cement composite properties. The study has been conducted by different experimental trials by varying the fiber content percentage and keeping other materials constant. SEM tests are performed for micro scale analysis.

1.4.1 Rationale Behind Variable Selection

Fibers are shortlisted based on the superior mechanical and physical properties comparison with other fibers. Fly ash is chosen because it is readily available, has adhesive properties that increase compressive strength, while fibers are chosen because they have the ability to resist the development and spread of cracks while improving mechanical properties, creating the composite more resilient.

1.5 Brief Methodology

In this experimental study, bendable composite will be produced with local available material and the mechanical, dynamic, absorption properties of PC and bendable composite ECC having fiberglass fiber and polypropylene fiber with cement partial replacement of class-f fly ash and superplasticizer will be determined in laboratory. For production of bendable composite fiberglass fiber and polypropylene fiber will be used. Both fiber lengths are kept 6mm long. The fiber length is shortlisted based on literature review [1–3, 6, 8, 10, 12, 14–22]. Fiberglass and PP fibers proportion combine is kept 1%, 1.5%, 2% by volume in bendable concrete according to [1, 2, 6, 14].

Fly ash is used in addition. The PC composite ratio is 1:2 for cement and sand. Two water/cement ratio are used, 0.45 for PC and 0.30 for Bendable Composite. The ratios of mix design are taken from literature for good strength achievement of bendable composite. The mixing is done starting with dry mixing of cement, fly ash, sand for 1 min and then water with super plasticizer will be added and mixing will be continued for 3 min. Super plasticizer dosage is kept between 1.5% by weight of binder. Fibers is added at the end to achieve uniform dispersion and mixing will be done for 5 min at high speed. Samples prepared will be cured for 28 days and then tested for mechanical and absorption properties of bendable composite.

1.5.1 Experimental Setup

The ASTM C78 test method uses a straightforward flexure element with three point load application to assess the flexural strength of composite Findings are given as modulus of rupture (MOR), a measure of a concrete sample's flexural strength immediately before it crosses yielding point. To calculate the MOR, a testing equipment that can apply and monitor loads at a constant rate without interruption with three-point flex assembly in accordance with the ASTM C78 standard is employed. The specimen is supported on the ends in the apparatus assembly and the load is applied through single mid-point. This setup is referred to as three point flexure strength test of concrete specimen.

1.6 Novelty of the Work, Research Significance, and Practical Implementations

In different studies and experiments it was found that load bearing capacity remarkably improved with addition of polymer fibers in concrete [3]. Mechanical properties notably enhanced with inclusion of polymer micro fibers in concrete [12]. The usage of fiberglass and Polypropylene fiber in bendable composite hasn't been studied to the best of author's knowledge. Current study is aimed to investigate the mechanical properties and microstructure of bendable composite made of fiberglass and polypropylene fiber.
Substances used in bendable composite will aid in the creation of environmentally friendly, crack-resistant durable concrete for use in structural applications [7]. The construction industry can greatly benefit from utilizing bendable composite, thanks to the readily available glass and PP fibers that enhance the mechanical properties of concrete. By somewhat using secondary cementitious material in concrete, this will contribute to reducing emissions brought on by the cement industry [19]. At the same time, using textile fibers in concrete will assist to prosper the textile industry with a way to construction. If the outcomes are encouraging, stronger and more environmentally friendly structures will be built.

Previous research has involved the making of bendable composites using a combination of PVA fiber and varying ratios of cement, sand, fly ash, and superplastisizor in the developed countries. However, it is worth noting that PVA fiber is costly to be used in developing countries, because specific material is to be imported costs more in the developing countries [8]. Hence, there is a significant potential to explore alternative, cost-effective polymer fibers that are locally accessible for fabricating bendable composites in the developing countries and assess its capability for structural elements. The primary objective of this study is to develop bendable composites using readily available materials from the local region and investigate their specific structural applications in greater detail. Using local materials in ECC construction reduces the carbon footprint, aligns with eco-friendly practices, lowers costs, and promotes skills development for the local economy.

After results are analyzed, distinct combinations of fiberglass and pp fiber are proposed. Recommendation from this study are made for specific application in construction projects. This research will provide guidelines which will help in solving construction sector problems with solutions, which will make the construction sustainable.

1.7 Thesis Outline

This thesis includes six chapters. That are:

Chapter 1 includes introduction. It covers the background, research motivation, problem statement, and overall and specific aims of this research, scope of work with study limitations, brief methodology, and thesis outline.

Chapter 2 consists literature review. It comprises of background, nature of bendable composite and conventional concrete, use of local material for producing bendable composite, application of bendable composites in structural elements, summary.

Chapter 3. This chapter consists of the experimental scheme, raw ingredients in concrete, mix design casting of specimens, testing, and summary of chapter 3.

Chapter 4 includes the results obtained from tests and their analysis. It describes the background, dynamic properties and mechanical properties of the mixes (PC, bendable composite), miscellaneous properties (water absorption, linear shrinkage, and mass loss), fractured surfaces of tested specimens, and summary of chapter 4.

Chapter 5 explains the guidelines for practical implementation, it has background, optimum combination of fiberglass fiber lengths, application of this research in real life, and summary of chapter 5.

Chapter 6 consists of conclusions and future recommendations.

Chapter 2

Literature Review

2.1 Background

In 1990 bendable composite was invented at university of michigan by prof Victor C. Li [3]. The composite exhibited strain hardening effect due to inclusion of polymer fiber that is polyvinyl alcohol fiber along with fly ash, cement, sand and superplasticizer. No aggregates were used in this composite. since conventional concrete has flaw due to brittle nature it has less tensile strength and therefore crack formation is more often, durability of concrete is less. Bendable composite is technically termed as engineered cementious composite ECC. The key factor of ECC is micro mechanics based criteria parameters. PVA fibers are expensive therefore local available cheap polymer fibers can be used to produce bendable composite.

2.2 Nature of Bendable Composite and Conventional Concrete

Traditionally, structural engineers have employed concrete primarily for its capacity to withstand compressive loads. Nevertheless, in real-world conditions, external factors such as shrinkage, chemical deterioration, and exposure to heat can subject concrete to tensile stresses [23]. Notably, concrete's tensile strength is merely 10% of its compressive strength. The core limitation of concrete lies in its brittleness, resulting in structural damage, degradation, cracks, and the need for frequent repairs of structural components [17]. Carbon dioxide emissions from cement manufacturing and use in building structures are significant and are almost on par with clinker production. This method uses a tremendous amount of energy, which has a negative impact on the environment [24]. Engineered Cementitious Composite, often referred to as bendable composite, is created by blending high-tensile synthetic polymer fibers from the textile industry with concrete components, excluding coarse aggregates, while incorporating fly ash and superplasticizer [25]. This composite boasts exceptional durability, self-healing capability, and remarkable resistance to shrinkage, impacts, and fire [26].

Bendable composites, also known as ECC, are fiber-reinforced materials exhibiting strain-hardening behavior and the development of multiple fractures, as documented in [27]. ECC can achieve a remarkable strain capacity exceeding 3% and maintain fracture widths below 100 micrometers under tension, provided suitable micro-mechanics-based design criteria are applied [22]. These fiber-reinforced cementitious composites, renowned for their exceptional strain-hardening capabilities and high mechanical performance, have found extensive applications in curbing crack propagation and mitigating the brittle failure often seen in conventional cement-based materials [28]. ECC displays several percent tension strain-hardening response with comparatively little fibre dose, typically 2% by volume [29]. Under tensile and bending loads, typical ECC demonstrates effective energy dissipation and the formation of numerous fine fractures [5]. Fibers are incorporated into concrete to enhance its resistance to impact and abrasion, reducing cracks resulting from drying and plastic shrinkage [10]. These micro-cracks in ECC, typically less than 100 micrometers wide, possess self-healing capabilities when exposed to moisture [8]. ECCs exhibit a tensile strength of approximately 4-12 MPa and a mid-point beam deflection range of 4-7 mm. Furthermore, ECCs outperform regular concrete mixes in terms of freeze-thaw resistance [15]. The strength criteria regulates the fracture initiation mode according to the micro-mechanics of ECC material, whereas the energy criterion controls the propagation of crack modes [13]. Among these, the inter-facial friction bonding strength is a crucial measure since it has an impact on the fibre bridge stress, fracturing spacing, and ECC's crack strength. According to research, the inter-facial friction bonding strength decreases as fibre content rises [16]. The stress-strain curve of ECC is more similar to that of a metallic material. With a definite "yield" strength that is followed by tensile strain-hardening behaviour [23]. The stress-strain relationship during strain hardening can be roughly represented by a straight line with a slope lower than the elastic modulus, with the linear connection being punctuated by numerous load dips, the amount of which depends on the specific ECC.

2.2.1 Bendable Composite Micro mechanics

The ECC design to obtain superior tensile ductility and strain hardening characteristic relies heavily on the micro-mechanics of ECC. It is largely possible to control the interactions among fibre and matrix in detail microscopic level, to provide ECC the desired macroscopic strain hardening qualities. The theoretical design criteria consist of two aspects. In adherence to the ECC pseudo strain hardening criteria, it is imperative that the maximum fiber-bridging strength exceeds the matrix rupture strength, and that the complementary energy of the fiber-bridging exceeds the peak of the crack toughness. This guarantees the initiation of cracks at multiple points and the establishment of stable, steady-state cracking conditions [3, 21, 30].

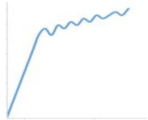
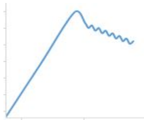
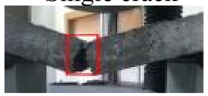
$$\sigma_o > \sigma_c \tag{2.1}$$

Strong chemical bonding between the fibre and the surrounding matrix is frequently anticipated for hydrophilic fibre systems, such as polyvinyl alcohol (PVA), and the fiber/matrix interface bond strength is governed by both the chemical adherence and friction [3].

The pullout stress increases as the fracture widens during the debonding stage. A rapid load decrease is seen when debonding is finished. This is a sign that the fibre pullout has reached the friction-dominant slippage stage and is due to a complete breakdown of chemical bonding between fibre and matrix. The slip-hardening reaction, which may be quantitatively quantified using the slip hardening coefficient, is the jamming effect of fibre fibrillation scraped by the matrix and collected in the interface tunnel [8, 13]. Because lesser fibre area is in touch with the matrix that surrounds it resulting in friction against fibre slippage, pullout load will decrease for an interface with constant fraction.

According to the strength requirement, the ultimate crack-bridge stress must be greater than the matrix initial cracking strength [31]. The energy criteria states that the fracture tip toughness (J_{tip}) of the matrix should be outperformed by the fibre bridging complementary energy (J_b‘) [32]. Fig 2.1 below represents relation among fiber bridging strength (σ) and opening of crack (δ). A higher bridging energy value enhances the likelihood of generating new fractures within an ECC specimen [21]. Micro-crack initiation resulting from flaws occurs at the cracking strength, while the steady-state propagation of flat cracks takes place under steady-state stress [33]. The ECC's tensile strain hardening effect is evident when both strength conditions are met, leading to the occurrence of multiple cracking. Matrix cracking strength depends on the matrix toughness Km, the fault size c, and, in the case of bridged flaws, the fibre bridging qualities. In order for any fracture to form without the specimen collapsing, the fibre bridging capacity must be greater than the cracking strength. The fibre content and characteristics, fiber/matrix interface, and snubbing effects all affect the complementary energy (J_b‘) and processing details may also have an impact on the fibre orientation [34]. While the ratio of bridging energy value to toughness tip of matrix value is known as the energy index (PSHE), the ratio of crack bridging stress value to matrix cracking strength value is known as the strength index (PSHS). The multiple-cracking behaviour of ECC may be quantified using the PSHS and PSHE values. In general, the PSHS and PSHE values should be larger than 1.3 and 3.0 [13, 22, 30], respectively, to guarantee the development of multiple-cracking in ECC specimens.

TABLE 2.1: Composite Properties for Characterization of ECC and FRC

S.No	Composite	Fracture Pattern	Composite Behaviour	Graphical Presentation	High Strength	High Deformation	Ref
1	Ideal EC-C/BC	Multiple Close racks 	Strain hardening		✓	✓	[1]
2	ECC/BC	Multiple Spaced cracks 	Pseudo Ductile		✓	✓	[34]
3	Acceptable ECC/BC or HPFR-CC/BC	Single crack 	Pseudo Ductile		✓	✓	[73] [46] [54]
4	FRC	Single crack 	Low ductility		X	X	[75]
5	PC	Broken in two Piece 	Brittle		X	X	[75]

Note: *Engineered Cementitious Composite (ECC) = Bendable Composite (BC) = High Performance Fiber Reinforced Cement Composite (HPFRCC). The Parameters and data for the characterization are derived from the referenced studies.

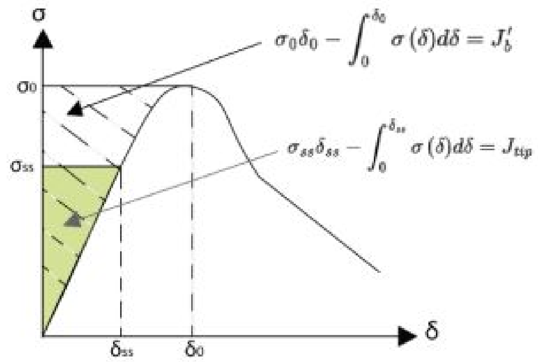


Figure 2.1: Fiber bridging Strength Vs opening of crack

The stress and crack opening interaction forms the engineered cementitious composite constitutive law and it is derived based on the analytic probability of fracture mechanics and micromechanics [20].The volume fraction, fibre length, diameter, elastic modulus and tensile strength are used to describe the fibre. The elastic modulus and fracture toughness are used to describe the matrix. The frictional stress, chemical bond and apparent fibre strength are used to define the fiber-matrix interface [35]. When a fibre is implanted in a cementitious matrix, its strength is diminished, which is shown by the apparent strength [22, 36]. The micromechanical model employed here is primarily focused on obtaining pseudo strain-hardening in tension in ECC materials since the limited tensile strain capacity of most cementitious materials is regarded as the bottleneck feature to achieving improved structural performance.

2.2.2 Cracking Phenomena

ECC's tensile strain-hardening behavior, as observed in references [2, 3], arises from the presence of multiple steady-state flat cracks. These cracks initiate at fault sites and extend through the matrix under sustained ambient loading. The term "complementary energy of fiber-bridging" refers to the energy input from external forces minus the energy stored in the fiber-bridging. To maintain steady-state cracking, the system's net available energy must surpass the fracture tip toughness, ensuring continuous crack expansion under uninterrupted ambient loads, as discussed in references [5, 7]. Another essential condition for the formation of numerous steady-state fractures in ECC is that the composite's tensile fracturing strength must exceed the fiber-bridging strength, as indicated in reference [20].

A criterion based on strength ensures that fractures can initiate from various rupture points, while the energy-based condition for steady-state fracturing delineates the process of crack propagation [10, 12].

The addition of different types and sizes of fibers can result in diverse inhibitory effects on crack propagation in concrete. Combining steel and polymer fibers in ECC, some researchers observed a synergistic effect that led to significantly reduced fracture widths and decreased drying shrinkage [8]. In ECC, the primary factors contributing to crack initiation and growth are internal pores and the interactions within the sand and cement mixture [16]. One of the most crucial factors affecting the durability of both structures and materials is the crack width since it directly influences the coefficient of permeability and self-healing capabilities of materials. The crack interval and crack breadth of the composite decrease as the frictional contact between the fibres and the matrix increases while the length to width ratio of the fibres increases [17].
Moreover multiple cracks formation are considered an ideal condition for ECC failure [37]. The fracture behaviour is function of fibre content and characteristics, fiber/matrix interface, fiber-matrix inter-facial bondage [38]. Polymer fibers are preferred due to good fiber characteristics and matrix interface [39]. As the fiber content, characteristics , fiber/matrix interface and fiber-matrix inter-facial bondage changes the mechanism of failure will change from multiple closely spaced fractures to openly spaced fractures and continue till single crack formation [40]. Mostly FRC materials exhibit single crack formation but with low ductile failure mechanism. ECC may consists of single crack formation but with pseudo-ductile failure mechanism [41]. Table 2.1 displays composite properties used to characterize ECC and FRC, encompassing attributes such as fracture pattern, material behavior, strength, and deformation. Ideal ECC composite exhibits Multiple closely spaced cracks, strain hardening behaviour with high strength and high deformation. In comparision to prior, moderate to low quality ECC composite

exhibits multiple spaced fractures to single crack with pseudo ductile behaviour, high strength and high deformation value [42]. While FRC has single large crack and low ductile failure with no high strength and high deformation [43] [44].

2.3 Suitable Material for Producing Bendable Composite

As cracks initiate within the matrix, particularly in the post-cracking region, the primary function of the fibers within the matrix shifts to fiber crack bridging, encompassing both crack limitation and stabilization processes [15]. ECC, reinforced with PVA fibers boasting a tensile strength of 1,600 MPa, exhibited a tensile strength of 4.5 MPa and a tensile strain exceeding 4%. ECC exhibited a tensile strength value of 3.6 MPa and tensile strain capability above 3.9%, when polypropylene fibres with tensile strengths of 800 MPa–900 MPa were utilised to further reduce the cost of the material [17]. The characteristics of the fibres have a considerable impact on ECC performance. Because of the PVA fibre hydrophilic nature, the chemical bond formed among the fibre and the matrix with no prior treatment (which includes an oil coating and the addition of an air-entraining agent) is very strong. This is not preferred because it can cause early fibre breaking before using the full potential of the fibre reinforcement. In contrast, PE fiber's hydrophobicity raises the risk that it won't be able to sufficiently endure and distribute shear stress, which might result in early debonding. By boosting interfacial bonding capacity and compression strength, this may be inhibited and the multi-cracking behaviour is accomplished. Compared to PE fibers, which exhibit a tensile strength ranging from 2500 to 3800 MPa, PVA fibers possess a relatively lower tensile strength, ranging from 800 to 1600 MPa. The high tensile strength, elastic modulus, and hydrophobic characteristics of PE fibers, all essential for structural reliability, result in PE-ECC displaying greater tensile ductility compared to PVA-ECC, boasting a tensile strain capacity exceeding 4% [18, 20]. Table 2.2 shows attributes of different polymer fiber. Coarse aggregates are not used in ECC because it enhances the fiber bridging mechanism to work as fiber dispersion and fiber clumping is improved [45]. ECC materials have high levels of cement which are 2-3 times greater than conventional concrete due to the absence of coarse particles [30]. Coarse aggregates toughen ECC, delaying cracks and reducing ductility. ECC opts for fine silica sand (S/B ratio of 0.37) instead to maintain stiffness, volume stability, and enhance work-ability [46]. Several research have suggested utilising inert fillers like limestone powder as well as supplemental cementitious ingredients including fly ash (FA) and powdered furnace slag as a partial replacement for cement in order to increase the greenness of ECC [47].

Table 2.2: Polymer fiber and their attributes

Sr.No	**Fiber**	**Properties**	**Ref**
1	Poly vinyl alcohol Fiber	High tensile strength, ductility, Superior crack resistance, Good molecular bond strength.	[10]
2	Poly ethylene Fiber	High energy absorption, high toughness index, economical, good flexural strength	[5]
3	Steel Fiber	High tensile strength, high toughness index, ductile, Flexural Strength, Fatigue Endurance, Impact Strength, Shear Strength, Abrasion, Skid Resistance	[2]
4	Glass Fiber	High stiffness, High strength, low density, relatively low cost, and high chemical resistance.	[48]
5	Polypropylene Fiber	high toughness, low tensile strength and modulus of elasticity, hardness, economical	[49]
6	Carbon Fiber	higher tensile strength, lower specific weight and corrosion resistance, expensive.	[10]

Class F FA is being widely used to replace large amounts of cement to make envoirment friendly ECC composite with good tensile strain capability [50]. It is indicated that increased FA concentrations are efficient in lowering fracture breadth (due to the higher fiber/matrix friction connection) and dry loss of volume,

TABLE 2.3: Results achieved using polypropylene fiber in composites

Fiber	**Matrix**	**Fiber-reinforced composite property**	**Value achieved**	**Application**	**Ref**
Polypropylene Fiber	OPC,Flyash, Silica fume,Crum rubber, Silica sand.	Tensile Stress.	2.24-3.87MPa (2.42–10.39% Strain Capacity).	Plain Composite	[49]
Polypropylene Fiber	OPC,Flyash, Lime stone,Silica sand.	Tensile strength.	3.2-4.25MPa (3.12–10.2% Strain Capacity)	Plain Composite	[51]
Polypropylene Fiber	OPC,Silica fume, Natural sand	Tensile strength.	4.31-5.71MPa (2.25-10.23% Strain Capacity)	Plain Composite	[52]

as well as boosting the ductility of ECC. The PVA or PE fibres that were often used in ECC are substantially more expensive than steel fibres while PP fibers are 7 times less expensive then PVA fibers. According to Wang [9] et al., using PP fibres in place of PVA can lower the cost of fibres.

Typically, ECCs are formulated with polyvinyl alcohol (PVA) and polypropylene (PP) fibers, commonly reaching a strain capacity of 3% to 5% [11]. Other polymer fiber are available that can be used in ECC, which can exhibit strain hardening capability and pseudo ductility in composite. Glass fiber and Polypropylene fiber are abundantly available in local textile market. Glass fiber has high tensile strength and modulus of elasticity while PP fiber has greater tendency of elongation. Both the fibers has hydrophobic nature and good properties for inducing strain hardening and multiple cracking phenomena [9]. Table 2.3 represents the results gained while using PP fiber.

2.3.1 Material Used in Different Studies

The different material combinations which are used in different studies for making of bendable concrete are as following. Cong Lu et al [1] used a combination of PVA and PET Fiber with ordinary portland cement, fine aggregate silica sand, water, class f fly ash with 10% cement replacement and polycarboxylate superplasticizer for making bendable composite. Kai Zhang et al [2] produced bendable composite using steel fibers, ordinary portland cement, silica sand, water, class-f fly ash, and polycarboxylate (Sp). H. Zhou et al [5] prepared ECC using polyethylene PE fibers with cement, silica sand, water, class f fly ash, and polycarboxlic acid as water reducing admixture. M. Chen et al [6] used PVA fibers with ordinary cement, Silica sand, water, low calcium fly ash and polycarboxylate (Sp). F. Dong et al [14] prepared high strength ductile composite using PE fiber with ordinary cement, silica sand, water, fly ash and Super plasticizer. Table 2.4 presents different materials used for producing ECC.

For increasing the fracture resistance and tensile qualities of ordinary concrete, researchers have suggested a number of fibres, including glass (GF), steel (SF), carbon (CF), polypropylene (PPF), and polyvinyl fibres (PVA), among others [53, 54].

It has been shown that combining multiple types of fibers, varying in lengths, diameters, elastic modulus, or tensile strengths, can result in composites displaying enhanced strain hardening behavior, increased ultimate strength, and improved strain capacity compared to composites containing only a single type of fiber [8]. The smaller diameter polypropylene fibers in PPGF fill gaps left by larger diameter glass fibers, lowering porosity in hybrid fiber concrete compared to single-fiber concrete, highlighting its beneficial hybrid effects [55]. The integration of both low and high modulus fibers in cementitious composites has shown an improvement in strain capacity [56]. Nevertheless, the choice of such fibres is largely based on their intended application. Concrete's flexural strength is influenced by the cement quantity, with glass fiber exhibiting a more significant impact compared to compressive strength, as observed in prior studies.

TABLE 2.4: Different material composition used for ECC

Sr No	**Fiber/Length**	**Fiber Tensile strength**	**Cement**	**Flyash**	**Sand**	**Superplasticiser**	**W/b Ratio**	**Ref**
1	PVA/12mm, PET/12mm	950MPa, 900MPa	OPC	Class F	Silica sand	Polycarboxlate SP	0.30	[1]
2	Steel/30mm	1570MPa	OPC	-	Normal sand	Polycarboxlate SP	0.35	[2]
3	PE/ 12mm	3000 MPa	OPC	Class F	Silica Sand	Polycarboxlate SP	0.30	[5]
4	PVA/ 12mm	1560 MPa	OPC	Class F	Silica sand	Polycarboxlate SP	0.28	[6]
5	PVA/ -	-	OPC	Class F	Silica sand	Polycarboxlate SP	0.30	[7]
6	PE/18mm	2400MPa	OPC	-	Silica sand	Polycarboxlate SP	0.30	[12]
7	PE/12mm, Steel/13mm	3000MPa	OPC	Class F	Silica sand	Polycarboxlate SP	0.24	[8]
8	PE/18mm	2900MPa	OPC	Class F	Silica sand	Polycarboxlate SP	0.32	[13]
9	PE/6mm	3000MPa	OPC	Class F	Silica sand	Polycarboxlate SP	0.26	[16]
10	PE/13mm	3200MPa	OPC	-	Silica sand	Polycarboxlate SP	0.38	[17]
11	PE/6mm	3000MPa	OPC	Class F	Silica sand	Polycarboxlate SP	0.26	[18]
12	PE/18mm	3000MPa	OPC	Class F	Silica sand	Polycarboxlate SP	0.20	[19]
13	PVA/12mm	1631MPa	OPC	Class F	Silica sand	Polycarboxlate SP	0.42	[20]
14	PVA/8mm	1620MPa	OPC	Class F	Silica sand	Polycarboxlate SP	0.27	[22]
15	Basalt/9mm	2230MPa	OPC	Class F	-	Polycarboxlate SP	0.20	[28]
16	PVA/8mm	1600MPa	OPC	Class C	Silica sand	Polycarboxlate SP	0.25	[29]
17	PE/12mm	3000MPa	OPC	-	Silica sand	Polycarboxlate SP	0.35	[24]
18	PE/-	3000MPa	OPC	Class F	Silica sand	Polycarboxlate SP	0.32	[57]
19	PVA/8mm	1600MPa	OPC	Class F	Silica sand	Polycarboxlate SP	0.11	[58]
20	PVA/8mm	1600MPa	OPC	Class F	Silica sand	Polycarboxlate SP	0.32	[45]

This influence is cumulative over time [59]. Considering the mechanical and physical properties of the above mixes materials, local materials with same physical and mechanical properties shall be selected for this composite.

2.4 Application of Bendable Composites in Structural Elements

The creation of Engineered Cementitious Composites (ECC) would lack significance without practical applications. ECC finds multiple practical uses in the field. Firstly, it provides an opportunity to correlate ECC's high tensile strain ductility with enhanced structural performance. Secondly, field applications showcase ECC's unique attributes, which are unattainable with conventional concrete. Thirdly, the real-world implementation of ECC in structures serves as valuable feedback for ongoing material development and enhancement. ECC has been utilized in various large-scale applications in countries such as Japan, Korea, Switzerland, Australia, and the United States.

2.4.1 Building Infrastructure

ECC coupling beams were used in the building cores of the 60 floor Kitahama Tower, Osaka, the 41 floor Nabule Tower, Yokohama, and the 27 Floor Glorio-Tower ,Central Tokyo. On each story, the building's architecture incorporates two or four ECC connection beams. Previously Super beams are used in the building's super frame design [36]. For the structure to self-center, the ends of the beams are damper-connected to the tops of massive columns. High ductility, energy absorption, and damage tolerance properties are provided by the new design's R/ECC connecting beams in the building core [60].

Cai et al [61] investigated the connection among ECC compositeand steel reinforcement and contrasted it with conventional concrete. It was determined that the link among the steel and ECC composite was stronger than the bond between concrete and ordinary steel. Lee et al [62] investigated the bond-slip performance to forecast the bond strength of ECC composite indicated that it had a 14% improvement in maximum bond strength. Fang et al [63] experiment used ECC composite in the junction between a beam and a column that was exposed to cyclic stresses. It was determined that the addition of ECC composite to the beam-column junction significantly increases its ductility, load-bearing capability, and energy dissipation. Experimental investigations into the cyclic behavior of steel-reinforced ECC columns and frames further validated that the structural integrity could be better preserved when ECC replaced conventional concrete [64]. Poongodi et al [14] came to the conclusion that ECC composite beams may maintain tension loads even after cracks occur, and they can also carry more weight before failing in the compressive region under loaded spots. The enhanced load-carrying capacities with ECC material are evident through its strain hardening and multiple micro-cracking behavior [65]. In comparison to the RCC beam with stirrups, the reinforced engineered cementitious composite beams showed greater ductility indices [60]. When compared to regular concrete, the bonding-slip ability and strength of the bond among steel and ECC composite were shown to be superior [14]. In contrast to traditional concrete structures, the assessment led to the conclusion that R/ECC members exhibit superior loading capacity and energy-dissipation capabilities, primarily attributable to the exceptional ductility of the ECC material [66]. ECC panels have been proposed by Zhang [36] as a possible option for the outside protective layer. Steel wires that extend through the polyetheylene insulating layer are used to secure the exterior wall assembly to the structural R/C wall. This application makes use of ECC's resistance to drying shrinkage as well as thermally induced cycles of both tension and compression. ECC-cladded exterior insulation walls have been used in a number of structures in Shandong and Hebei, China, since 2014. In Hong Kong housing projects to stop incipient spall from dislodging, Cheung et al. [67] recommended coating the entire building surface with a thin layer of ductile ECC. A 5–10 mm ECC layer, according to experimental testing, was sufficient.

ECC has ductile properties that have greater then 0.03 strain and fine defects of 60 um, making it suitable for retrofitting structural parts, particularly to improve seismic behaviour [15]. Additionally, it could be utilised to prevent the concrete cover from spalling, which weakens concrete buildings early by causing embedded steel bars to corrode.

2.4.2 Transportation Infrastructure

Yanhou Tunnel, China, explosion caused by burning process led to serious damage to the tunnel lining. Bendable Composite was designed and applied to improve the tunnel strength [6]. In 2005, Hokkaido, Hokkaido, Japan's Mihara Bridge, a km-long span, opened to traffic. Around 800 m3 of ECC material make up the steel-reinforced roadbed. The amount of material needed during construction was reduced by 40% as a result of the tensile ductility and effective fracture control behavior of ECC [28].

On bridge decks, expansion joints are thought to be crucial for preventing concrete deck cracking brought on by temperature-related elongation and contraction of the holding girders [68]. Using an ECC link-slab to replace the expanding joint and a portion of the neighbouring concrete slabs is a feasible solution to the expansion joint issue [69]. Zhang et al [41] presented the equivalent ECC link-slab idea used for paving roads. This application aims to lessen joint damage and extend the useful life of pavements. In Beijing, this idea has undergone field testing. A comparable application of ECC link-slab was made on a city motorway in Japan [40].The seismic performance assessment results suggest that the ECC material-reinforced bridge exhibits a remarkable ability to nearly return to its initial position following earthquakes, thanks to the ECC material's resilience. In contrast, the RC bridge consistently experiences substantial permanent residual deformation [70]. The Tokai Hokuriku Motorway in Japan includes a significant portion of the second-longest (10.7 km) road tunnel in the world, the 12.3 m-diameter Hida tunnel, which was finished in 2008, ECC was used in tunnel lining [28]. The Tennou JR tunnel underwent retrofit following the 2004 Niigagta Chuetsu Earthquake.

The concrete lining of the 8.6 metre diameter railways tunnel has surface spalling and cracking.

2.4.3 Water Infrastructure

Using ECC, the Mitaka Dam close to Hiroshima was restored in 2003. The dam's surface, which was 60 years old at the time, had significant fractures, spalling, and water leaking. ECC was sprayed over the 600 m2 surface area in a 20 mm thick coating [7]. Block joint repair of Hydraulic Power Plant Hohenwarte II, Thuringen, Germany was conducted using ECC at a location of visible cracks and concrete spalling [36]. On dam's surface upstream side a section of 17x3.5 m in height and width was replaced with thickness of 30 to 50 mm sprayable ECC. In order to improve the bonding amongst ECC and old concrete, loose fragments on the surface of concrete were removed before wet ECC spraying.

Irrigation channels surface usually become abraded and cracked. The surface of material was repaired to enhance its service life through utilizing the freeze thaw, fracture resistance and narrow crack width properties of ECC. In 2005 central main channel in Shiga and Seridanno channel in Toyama, both in japan were repaired using ECC application [36]. They had deteriorated to 1mm wide concrete fractures and concrete spalling due to exposure of coarse aggregate to the flowing water.

2.5 Summary

It is clear from the explanation above that adding textile waste to concrete can enhance its qualities. To stop cracks from spreading, concrete's mechanical and dynamic qualities must be improved. Wastes of textiles are seriously harming the environment. It is concerning when textile waste are burned or dumped. It is possible to use these leftovers in concrete. This chapter of research leads to the conclusion that textile wastes can reduce the shortcomings of concrete. Concrete's splitting tensile and flexural strength can be enhanced using polymer fibres. The performance of concrete can be improved by preventing both macro and micro cracking by the utilization of polymer fibres of different lengths.

Chapter 3

Experimental Methodology

3.1 Background

Bendable Composite is a type of high-performance fiber-reinforced concrete that uses polymer fibers. The addition of polymer fibers results in improved mechanical properties, such as increased toughness, ductility, and crack resistance. According to various studies conducted in foreign countries, the bendable composite consists of following raw materials Polymer fibers, Ordinary Portland Cement, Fly Ash Class F, Sand, Superplasticizer and Water [71]. The mix design of bendable composites involves the careful selection of materials and their proportions to achieve the desired mechanical and durability properties. To evaluate the mechanical properties of bendable composite, various tests have been considered, flexural test, split tensile, Compressive strength, flexural strength test, Dynamic tests, Mass loss, Linear shrinkage and Water absorption. several tests are taken into consideration, when examining the impact of raw materials and polymer fibre combinations on concrete. Additionally, the shattered surfaces of the damaged specimens are also investigated. In this chapter, raw ingredients, Mix Design, methods of mixing PC and bendable composite, casting practices and methods of testing are deliberated in detail.

3.2 Raw Material

In the production of plain cement composite (PC), the ingredients include OPC cement, locally sourced sand, and potable tap water. In contrast, for creating bendable composite, the components consist of OPC cement, fly ash, sand, superplasticizer, and potable water, with the addition of synthetic polymer fibers [72]. Two types of fibers are used that are fiberglass and polypropylene fibers, which are available commercially. 6mm length of both the fibers are selected based upon their commercial availability [73]. With longer fiber lengths, the fiber

Table 3.1: Properties of Glass Fiber Polypropylene Fiber [52, 74]

Parameters	**Glass Fiber**	**Polypropylene Fiber**
Diameter (um)	20	12
Density (kg/m3)	410	910
Tensile Modulus (MPa)	1700	910
Youngs modulus (GPa)	72	9
Water absorption (%)	0	0.03
Elongation (%)	2	22
Specific gravity (g/cm3)	2.68	0.91

stress surpasses the fiber strength, making fibers more susceptible to rupture, and once ruptured, they can no longer effectively bridge cracks during propagation [75]. The incorporation of PP fibers enhances concrete's ductility, toughness, and impact resistance [76]. No added treatment has been conducted because there are no illustrative impurities on both the fibers.The aspect ratio of fiber glass and PP fiber is 300 and 500. The properties of glass fibers and polypropylene fibers are given in Table 3.1. Figure. 3.1 presents glass fiber and polypropylene fibers. For preparing ECC or bendable composite glass fiber and polypropylene are used. The lengths glass fiber and PP fibers used are 6mm respectively. Proportion of fiberglass and PP fiber is kept 1%, 1.5% and 2% as advised by [20][74][49]. Normal temperature tape water is used for preparing bendable composite and plain cement.

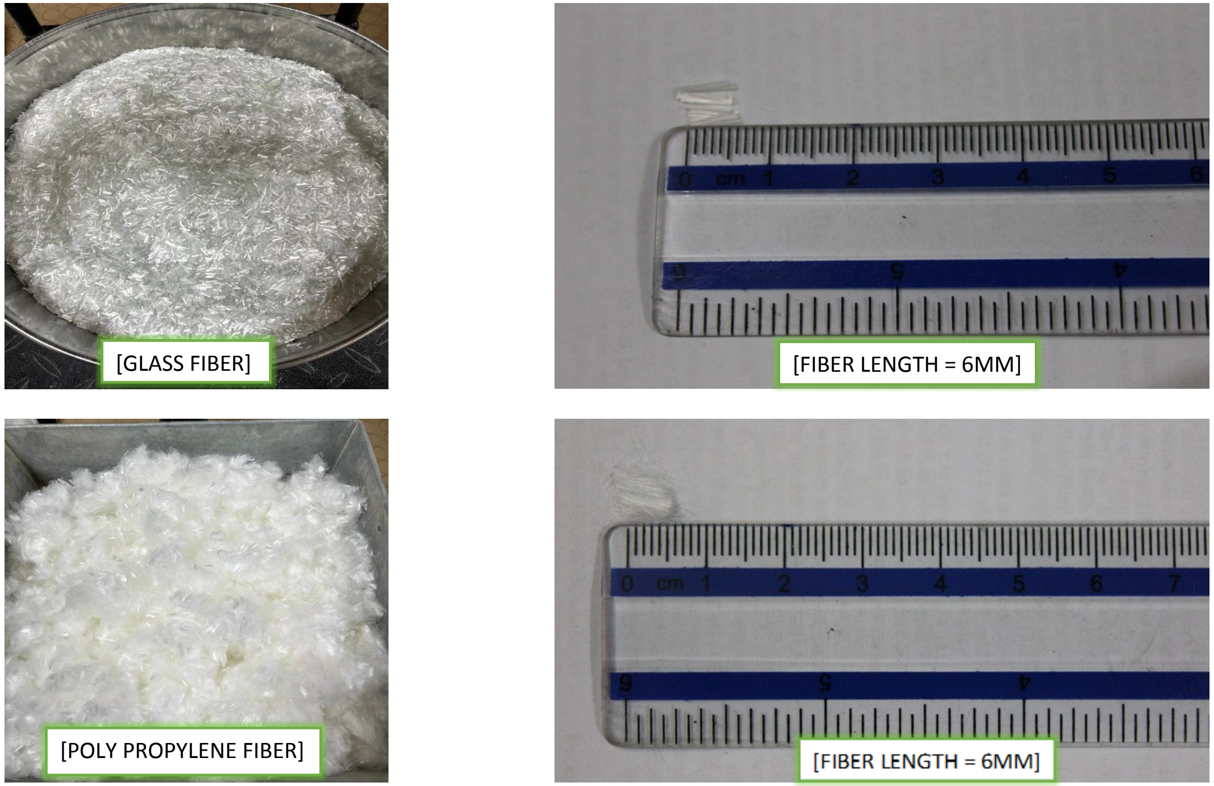


FIGURE 3.1: Depiction of Glass Fiber, Polypropylene Fiber and its Cut Lengths

Water/cement ratio has been kept different for plain cement and bendable composite specimens [15]. For plain cement water/cement ratio has been kept 0.55 while for bendable composite 0.30. The w/c for PC is 0.5 to 0.6 as reported by [15]. The fly ash used is class F type fly ash, locally available with chemical composition shown in Table 3.2. The chemical composition has been taken from the data sheet of manufacturer company and compared with different researchers data provided in literature. A commercially available, local market superplasticizer brand name Sika Viscocrete 3110, based on polycarboxylate, is employed to enhance the workability of the composite material.

TABLE 3.2: Chemical Composition of Cement and Fly Ash Class F [77, 78]

S.No	Chemical Composition	Cement(%)	Fly ash(%)
1	Calcium Oxide (Cao)	65.3	4.42
2	Silicon Dioxide (SiO2)	22.06	51.55
3	Aluminium Oxide (Al2O3)	6.13	33.32
4	Iron Oxide (Fe2O3)	2.57	3.34
5	Sulphur Tri-Oxide (SO3)	1.25	0.8
6	Magnesium Oxide (MgO)	0.81	0.75
7	Potassium Oxide (K2O)	0.45	0.073
9	Sodium Oxide (Na2O)	0.9	0.51
10	Titanium dioxide (TiO2)	1	0.08

3.3 Mix design, Making of specimens and Density finding

For making Plain cement composite (PCC) 1:2 (cement: sand) proportion is used, While creating ECC bendable composite 1:0.8:1.2 (cement: sand: fly ash) has been used as mentioned by [5, 7] [79]. For making of bendable composite or engineered cementious composite (ECC) the percentage of polymer fiber added is 1%, 1.5% and 2% by volume of concrete respectively in each batch of composite concrete for investigating the behaviour of composite with increase in fiber content [5–7, 12][16] [68, 80]. The fibers added are fiberglass and polypropylene fiber in combination of half of the fiber percentage mentioned in the respective individual batch. The fly ash content has been kept fixed in all batches according to the ratio proportion referenced by [5]. The type of Fly ash used is, class f based on its utilization in different researches [1] [5], [7],[8] and [81] . Sand is used in the composite according to the ratio. Super plasticizer is added in engineered cementious composite for achieving good work-ability. In this study high range water reducer (HRWR), Polycarboxlate based super plasticizer is used [7] [82] [83]. The content of super plasticizer has been kept 1.2% by weight of binder material according to [20].The water cement ratio has been kept 0.30 for engineered cementious composite based on different researches to achieve higher strength [5]. The addition of SP helps in achieving this low water cement ratio.

For making PC mix the material is placed in mixture and the water is added 60 seconds after the mixture drum starts rotation. The mixture is rotated for 5 minutes. After that slump test is performed to check the workability of mix. For preparing bendable composite (ECC) all the material in powder form i.e cement, sand and fly ash are stirred for one minute at low speed. Then all the liquids i.e water and super plasticizer were added and stirred for 3 minutes at high speed. After that the mix was stirred for 5 minutes at low speed after the addition of fibers [83] [84] [85]. Materials are arranged in layers during the production of bendable composite (ECC) to ensure proper mixing of dry materials. The BC is properly mixed using three sets of layers. The mixer machine is filled with a three batches of cement, sand, and fly ash layers. Then, the mixture machine is powered on. And when the machine starts, water is added with superplasticizer [86]. After the mixer has continuously rotated for three minutes, and the machine is then rotated for a further two minutes while performing a slump flow test to see whether the freshly created BC is workable. Slump flow test was conducted and composite paste were cast in molds, which were removed from molds after 24 hours. Upon drying the samples were kept in water curing tank at temperature 25 $\circ$C for 28 days. The samples were moved for testing after the curing duration was achieved.

The initial setting time of PPGF-ECC recorded was 65 minutes. This increase was due to use of superplastisizor and high volume fly ash.The remaining BC kinds used the same method, but with predetermined amounts of polypropylene and glass fibre.
Slump cone testing is done to determine whether a produced PC is consistent or workable [87]. Before pouring PC and BC into moulds, a slump test is always conducted. To determine whether fresh concrete is workable, the slump cone test is carried out in accordance with ASTM standard C143/C143M-15a. Consistency of the fresh composite is assessed using the slump cone test. The test is conducted using a slump cone with a bottom diameter 200 mm (8 in), a top diameter of 100 mm (4 in), and a height of 300 mm (12 in). The non-absorbent cone mould is required. Tamping rod has a diameter of 16 mm (5/8 in), a maximum length of 600 mm (25 in), and is hemispherical at both the ends. Three identical layers of concrete are used to fill the cone. Compaction is carried out after the first third of the layer has been laid down by randomly dropping tamping rods 25 times onto the layer's surface from a height of 25 mm (1 in). The cone's additional two levels are filled and pressed down using a tamping rod in a similar manner. The excess concrete was removed by hitting it with a tamping rod, and the surface was smoothed by sliding the rod on it. Cone of slump is there after raised vertically upward. The slump cone's concrete mould is next to the upside-down cone. In case of PC the tamping rod is positioned above the upturned slump cone so that its length may be measured over the composite slump using a ruler. To the best of the authors' understanding, there isn't a standard test that can be used to determine if fresh ECC is workable. The workability of all ECCs is therefore determined using the same process and test criteria. Table 3.2 displays the densities and slumps that were determined.

3.4 Testing Methodologies

Dynamic test, mass loss, water absorption test, linear shrinkage test, and mechanical tests are conducted in testing methods to identify various concrete properties.

Table 3.3: Specimen Label, Mix Ratio, Fiber Percentage, Fiber length, Slump values and Density of Composite

Specimens Labels	**C:S:F**	**Fiber Percentage by Volume of composite**		**Fiber Length (mm)**		**W/C**	**Concrete Slump value (mm)**	**Hardened Concrete Density (Kg/m3)**
		Glass Fiber	PP Fiber	Glass Fiber	PP Fiber			
PC	1:2	0	0	0	0	0.55	60	2337
BC1	1:0.8:1.2	0.5	0.5	6	6	0.30	195	1914
BC2	1:0.8:1.2	0.75	0.75	6	6	0.30	211	1911
BC3	1:0.8:1.2	1	1	6	6	0.30	205	1908

All of these tests are carried out in accordance with ASTM guidelines or as recommended by earlier researchers. For each test, an average two specimens are collected. The test apparatus for mechanical testing and dynamic tests are shown in Figures 3.3a and 3.3b. With the use of an accelerometer and a hammer, longitudinal, the lateral direction, and rotation frequencies are recorded in order to ascertain the dynamic parameters of conventional concrete, glass fibre reinforced concrete, and PP fibre reinforced concrete. Each of the aforementioned resonance frequencies is determined using one of three different test setup types.

In a longitudinal frequency setting, a hammer is struck against one sectional side of sample (that can be a cylinder specimen or beamlet specimen), while an accelerometer sensor is connected to the other. Accelerometer is positioned along the length of sample, 25 cm from the edge of the cross-section, and then a hammer stroke is applied adjacent to accelerometer sensor, along the opposite edge of the specimen to measure the transverse frequencies.

Accelerometer is attached in the same manner as it is set up in longitudinal setup in order to figure out torsional frequencies using third kind of test setup. But after that, the length of the specimen that is parallel to the accelerometer is where the hammer stroke is applied.

To investigate the mechanical characteristics of PC and bendable composite, compression test, split tensile test, and flexural tests are conducted. Cylinder samples are positioned vertically between the testing machine to serve as a model for a compression member as part of the compression test. For the splitting tensile, cylindrical samples are placed between testing plates. such that this configuration may monitor the splitting tensile characteristics. To acquire an accurate value for any findings from these tests, the average of two samples is used. In order to acquire precision and examine any deviation in findings, the average of the dynamic and mechanical characteristics results are taken.

3.4.1 Dynamic Testing

According to ASTM 215-14 Table 3.3, a dynamic test is conducted prior to destructive (mechanical) investigation of the samples. Hammer with accelerometer data are used to calculate responsive frequencies lateral (RFL), responsive frequencies transverse (RFT), and responsive frequencies rotational (RFR) [88]. Both beamlets and cylinders are used in the test. For the purpose of calculating the RFL, an accelerometer is attached to one side of the cross sectional area of cylinders and beamlets, and the other side of the cross section of the samples is struck with a hammer.

The accelerometer records the frequencies it sees and sends them to the computer that is connected to it. For cylinders and beamlets, the RFT and RFR connecting the accelerometer and hammer striking position procedures are different. For RFT, the accelerometer is mounted to the side of the cylinder indicating the cylinder length at least 25 centimetres preceding the edge. Then a hammer blow is delivered at the very same side that is facing the centre length of the cylinder. The accelerometer for RFR is mounted at the top and displays the cylinder length with the exact same distance from the edge as RFT. The strike is delivered at an accelerometer that is perpendicular to the opposite cylinder length edge. For the purpose of determining RFT, an accelerometer that is attached to one side length at same range as used for a cylinder is placed on the length of the beamlets from the outermost edge. Hammer blows are delivered at the length's centre on the same side that the accelerometer is mounted.

The accelerometer for RFR is fixed to the rectangle's top corner (the side facing of beamlet). Strike is made at the opposite bottom corner of the rectangle at sam same side in such manner that the line which connects the hammer striking and the point of accelerometer forms a rectangle diagonal. The damping ratio, dynamic modulus of elasticity, dynamic modulus of rigidity, and poisson's ratios are computed from these measured frequencies. These estimated parameters aid in understanding PC behaviour and resistance to dynamic loading, as well as that of bendable composite. These characteristics are essential for the construction of structures that will withstand earthquakes and dynamic loadings.

Table 3.4: Tests Standards and Study Parameters

Test	Allowed Standards	Focused Parameters	Additional Parameters Considered for this study
Compressive strength	ASTM C39	Compressive strength	Stress–strain curves, compressive pre-cracking energy absorption (CE1), compressive post-crack energy absorption (CE2), compressive total energy absorption (CTE), compressive toughness indexes (CTI), and modulus of elasticity (MOE).
Flexure Strength	ASTM C78 ASTM C1609	Flexure strength	Load-deflection curves, flexural pre-crack energy absorption (FE1), flexural post-crack energy absorption (FE2), flexural total energy absorption (FTE), and flexural toughness indexes (FTI).
Split Tensile Strength	ASTM C496	Splitting tensile strength (STS)	Load deformation curves, splitting tensile precracking energy absorption (SE1), splitting tensile post crack energy absorption (SE2), splitting tensile total energy absorption (STE) and splitting tensile toughness indexes (STI).

TABLE 3.5: Tests Standards and Study Parameters

Test	**Allowed Standards**	**Focused Parameters**	**Additional Parameters Considered for this study**
Dynamic Properties	ASTM C215-14	RFL, RFT and RFR, Damping ratio	No additional parameter studied.
Dynamic Properties	ASTM-C1548	Modulus of rigidity, and Poisson ratio	No additional parameter studied
Water Absorption,	ASTM C642	Water Absorption and Density	No additional parameter studied
Mass Loss test	ASTM C1792/1792-14	Mass loss versus time	No additional parameter studied
Linear Shrinkage	ASTM C157M-08	Shrinkage percentage	No additional parameter studied

3.4.2 Mechanical Testing

3.4.2.1 Compression Test

The compressive strengths of PC and bendable composite are measured using a Universal testing machine (UTM). On PC and bendable composite cylinders, the ASTM C39 test is conducted [89]. Compressive strength (C-S), Total Strain (e_o), compressive pre-crack (C1) and post-crack energy (C2), compressive total absorbed energy (CTE), and the compressive toughness index (CTI) of PC and bendable composite are among the parameters measured in this test. Plaster of Paris is used to cap the cylinder in order to distribute load evenly throughout it.

3.4.2.2 Split Tensile Test

Splitting-tensile test is performed in accordance with ASTM C496M-02. The test is carried out on the same UTM machine. The PC and bendable composite cylinders are subjected to the test. In case of the split-tensile test, cylinder caps are not necessary. Load-deformation curves, splitting-tensile strength (STS), splitting-tensile pre-crack energy absorption (SE1), splitting-tensile post-crack energy absorption (SE2), splitting-tensile total energy absorption (STE), and splitting tensile toughness indexes (STI) are computed from the results of this test [90].

3.4.2.3 Flexural Strength Test

Flexural testing is done in accordance with ASTM C78 criteria on the beamlets without reducing the moment of inertia for higher deflection. It uses a three-point loading system. The test is run on the PC and bendable composite beamlets.

The load-deflection curves, flexural strength (F-S), flexural pre-crack energy absorption (FE1), flexural post-crack energy absorption (FE2), flexural total energy absorption (FTE), and flexural toughness indexes (FTI) are the test parameters that were examined [56].

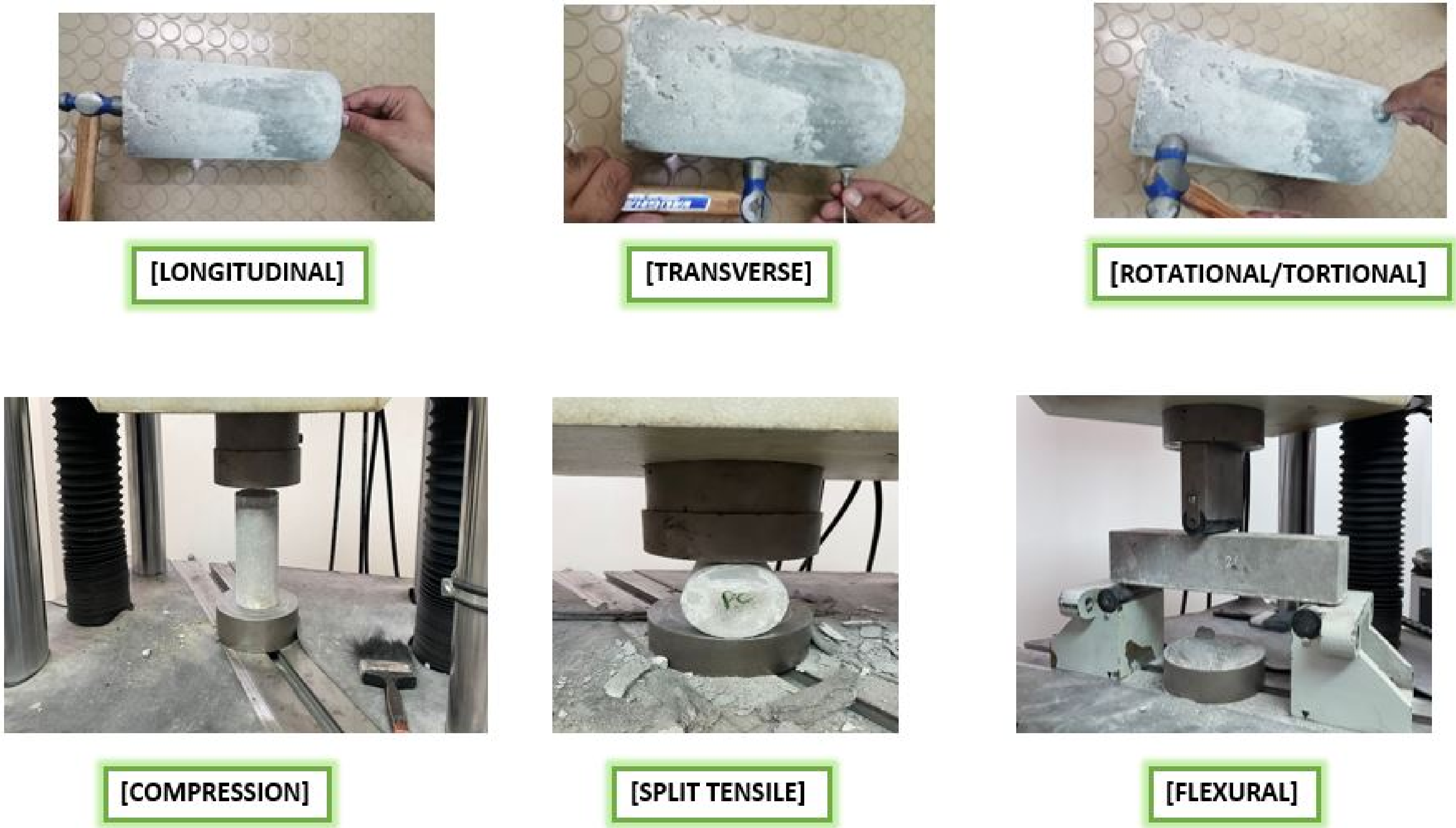


FIGURE 3.2: Dynamic and Mechanical Testing Setup

3.4.3 Miscellaneous Testing (Water Absorption, Mass Loss and Linear Shrinkage

Using ASTM C642 standard the Table 3.3 shown, the water absorption characteristics of PC and bendable composite are calculated. Specimens are first dried in the oven, after which they are submerged in water around room temperature. All sorts of specimens' water absorption properties are ascertained using this procedure [91].
ASTM C157/C157M08, following the OPSS standard LS-435, is employed to assess linear shrinkage by tracking and quantifying changes in specimen length. Prior to conducting the test, a reference line spanning 6 inches is marked along the samples' length. Subsequently, the length variation is determined in accordance with the specified procedure. The linear shrinkage is calculated by comparing the designated length before and after the test, expressed as a percentage difference, as outlined in references [92] and [93]. For the measurement of mass loss in PC and bendable composite, ASTM C157M-08 is employed. in reference line Variability and shrink are documented after completing the test process before being assessed. A specimen of each type is heated to a high temperature. Temperature is increased by 3 degrees Celsius every minute from 20 to 100 and held there for an hour. In order to get more accurate data, this is performed. To prevent thermal cracking, specimens are then cooled down at the same pace at 3∘C.

3.4.4 SEM Procedure

Scanning Electron Microscopy (SEM) creates detailed, magnified surface images, revealing composition and physical features. It employs electron beams from an electron gun, which are focused through lenses and apertures. SEM works in a vacuum to ensure high image quality by preventing interactions with molecules or atoms in the column. SEM considerations include sample size, shape, state, and conductivity. SEM on fractured surface of flexural beamlets were conducted. Nonconductive samples may need coating with materials like gold, silver, platinum, or chromium. Cleanliness is vital for clear imaging. Preserve details with fixatives or alcohol when needed. Ensure samples are completely dry in the vacuum to prevent water vapor interference with the electron beam and image clarity.

3.5 Summary

The production of bendable composite uses the mix composition ratio of 1:0.8:1.2. 0.55 W/C is utilised to produce PC, whereas bendable composite specimens require 0.30 W/C. In addition to 6 mm long PP fibres, 6 mm long glass fibres are also employed. Glass fibre makes up 1% of composite volume, while PP fibre also makes up 1% of composite volume. There are a total of 36 cast samples, 16 of which are cylindrical for a total of 4 combinations, 8 beamlets, and 12 slabs for a total of 4 bendable composite combinations. The determination of slump, dynamic, mechanical, and other tests for PC and bendable composite adhere to ASTM requirements. Chapter 4 goes into great discussion on the outcomes.

Chapter 4

Experimental Testing Outcomes

4.1 Background

Samples are prepared as described in Chapter No: 03. Ratios of Mix design 1:0.8:1.2 (Cement:Sand:FlyAsh) with 0.30 Water/Cement ratio are used in producing ECC. The fiber length used is 6mm for Glass fiber and Polypropylene fiber. In this chapter results of dynamic and mechanical characteristics along with SEM Images analysis are discussed in detail.

4.2 Dynamic Characteristics

To assess the impact of glass and polypropylene fibres on the characteristics of concrete specimens, the PPGF-ECC dynamic properties are examined. According to ASTM standard C215-14, the dynamic characteristics of samples of plain composite (PC) are determined. As there isn't a specific standard available to do so, therefore same standards guidelines are used to establish the dynamic attributes of PPGF-ECC.

Table 4.1 presents the dynamic properties calculated for both Portland cement (PC) and all combinations of Polypropylene-Glass Fiber Engineered Cementitious Composites (PPGF-ECC). To ensure accurate and representative results for each

Table 4.1: PC and PPGF-ECC Dynamic Properties

Concrete Specimens	Studied Parameter						
	RFL (HZ)	**RFT (HZ)**	**RFR (HZ)**	ζ %	**Ed (GPA)**	**Rd (GPa)**	**Poisson Rtio (-)**
Cylinder							
PCC	3107 ± 54	3196 ± 44	3151 ± 44	1.1 ± 0.025	1.5 ± 0.137	1.5 ± 0.10	0.28 ± 0.002
1% PPGF-ECC	4372 ± 49	4286 ± 22	4235 ± 22	1.3 ± 0.23	3.2 ± 0.093	3.1 ± 0.008	0.21 ± 0.008
1.5%PPGF-ECC	4561 ± 33	4982 ± 53	5082 ± 61	1.45 ± 0.924	3.1 ± 0.185	3.8 ± 0.299	0.20 ± 0.009
2% PPGF-ECC	5259 ± 66	5326 ± 74	5282 ± 54	1.6 ± 0.256	4.1 ± 0.160	4.1 ± 0.083	0.19 ± 0.006
Beamlets							
PCC	3445 ± 23	3414 ± 44	3474 ± 44	1 ± 0.116	21.8 ± 0.127	26.1 ± 1.03	0.26 ± 0.027
1% PPGF-ECC	4128 ± 67	3637 ± 44	3620 ± 62	1.33 ± 0.091	31 ± 1.07	28.2 ± 2.09	0.23 ± 0.002
1.5% PPGF-ECC	3728 ± 36	3522 ± 45	3531 ± 21	1.41 ± 0.250	25.3 ± 0.415	26.8 ± 0.28	0.22 ± 0.010
2% PPGF-ECC	3750 ± 29	3616 ± 53	3583 ± 25	1.61 ± 0.226	25.6 ± 0.09	27.6 ± 0.12	0.20 ± 0.001

PPGF-ECC specimen combination, an average of two values is taken. This approach helps establish an appropriate average for each corresponding dynamic property.Comparatively, the PC damping ratio (ζ) and PPGF-ECC mixtures at different percentages 1%, 1.5%, and 2% exhibits variations. The differences in damping ratio are as follows: the damping ratio of PC is 13.34% lower than that of 1% PPGF-ECC, 28.9% lower than that of 1.5% PPGF-ECC, and 43.35% lower than that of 2% PPGF-ECC respectively.

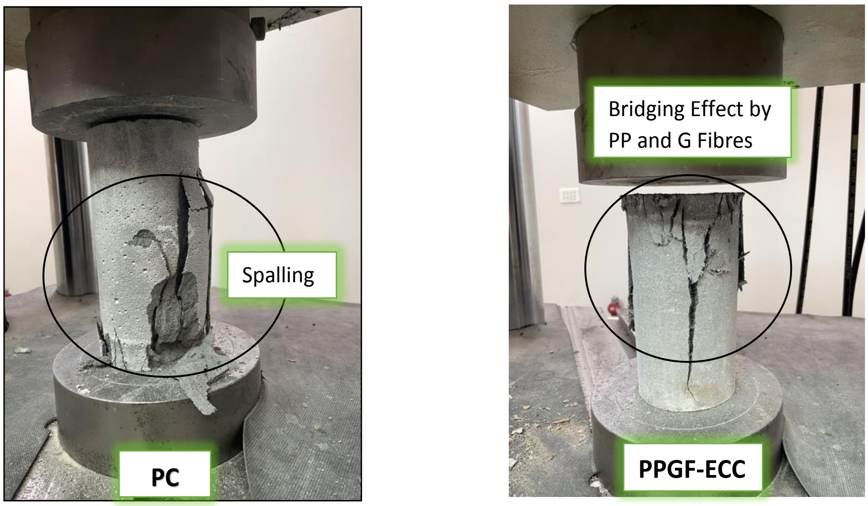
When considering beamlets, the damping ratios of 1% PPGF-ECC, 1.5% PPGF-ECC, and 2% PPGF-ECC exhibit increases of 29.8%, 37%, and 56.2%, respectively. It's noteworthy that the combination featuring 2% PPGF-ECC demonstrates the most substantial increase across all PPGF-ECC combinations. Conversely, for cylinder specimens with a consistent fly ash content, the increment in resistance against dynamic loading is observed with an elevation in the volume percentage of Polypropylene and Glass fiber. In the case of beamlets, specimens containing 2% fiber content exhibit superior resistance against dynamic loading when compared to PC specimens that lack both fly ash and fiber. This highlights that the incorporation of 2% fiber content contributes significantly to improved performance under dynamic loading conditions.

4.3 Mechanical Properties

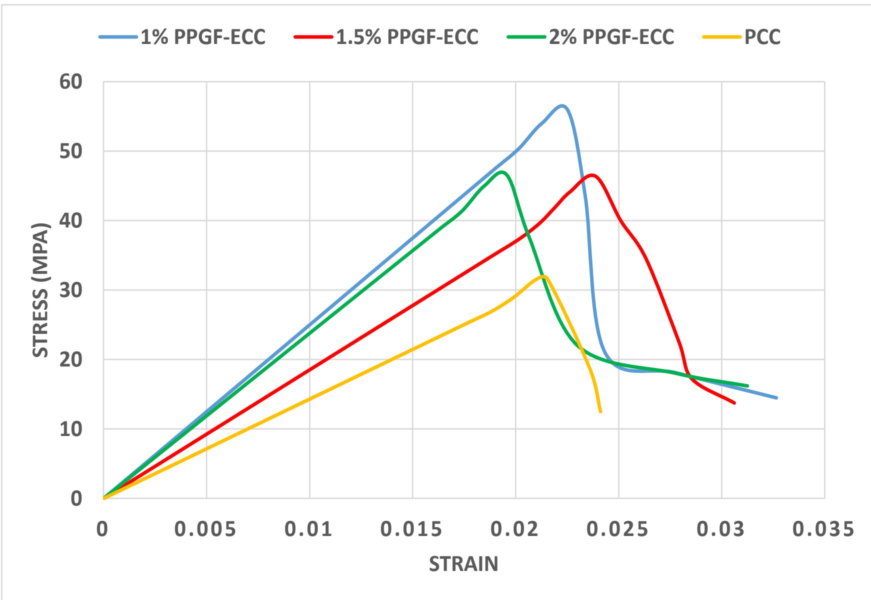
4.3.1 Compressive Properties

The stress-strain relationships of PC, 1% PPGF-ECC, 1.5% PPGF-ECC, and 2% PPGF-ECC are illustrated in Figure 4.1 (b). Observing Figure 4.1 (b), it becomes evident that among all PPGF-ECC variants and PC, the 1% PPGF-ECC exhibits the highest compressive strength (C-S) value. Notably, the compressive strength of 1% PPGF-ECC demonstrates an increase of 76.9%, whereas the strengths of 1.5% PPGF-ECC, 2% PPGF-ECC experience increases of 46.8% and 47.2%, respectively. Liu et al [94] have explored similar trend of (C-S) increase for PP and G fibers, in which 1% of both fibers have maximium compressive strength. Due to

their attributes such as high tensile strength, excellent dispersibility, and significant ductility, fibers when incorporated, helps in curbing the initiation and spread of cracks while enhancing the matrix's strength. Additionally, PP fibers have been reported to yield positive effects on the compressive strength of concrete [95].
Among all types of PPGF-ECC, the 1% PPGF-ECC exhibits the highest compressive strength. However, when the fiber percentage is increased to 1.5% in PPGF-ECC, the compressive strength value decreases by 20.5% compared to the 1% PPGF-ECC. Similarly, with a further increase in fiber percentage to 2%, the compressive strength of 2% PPGF-ECC decreases by 20.2% in comparison to the 1% PPGF-ECC. Zhang et al [96] reported increase in (CS) with 1% PP fiber and decreasing (CS) with 1.5% and 2% PP fiber due to randomly distributed fibers have the potential to reinforce the matrix and control crack propagation, thereby improving compressive strength. However, exceeding a fiber content of 1 vol % results in poor dispersion of the high-volume fraction of fibers within the matrix, leading to an increased presence of air bubbles and consequently reducing compressive strength. Excessive fiber content can significantly reduce concrete workability, compressive strength, and durability. Typically, the volume fraction of PP fiber is kept below 1% in concrete to ensure its positive effects on concrete performance are maintained [54]. Similar behaviour in compression is also denoted by Medina et al [97]. This trend is also observed in the case of PC, where there is no fiber content and the presence of class f fly ash. In this scenario, the compressive strength value decreases by 76.9% compared to the 1% PPGF-ECC, which includes 1% Polypropylene and Glass fibers along with 20% class f fly ash.
The compressive strength (C-S) values of 1% PPGF-ECC, 1.5% PPGF-ECC, and 2% PPGF-ECC surpass those of PC. This could be attributed to the presence of polypropylene and glass fibers, which act as effective crack arrestors due to bridging effect encountered in specimens failure. Table 4.2 provides the modulus of elasticity (MOE) values for both PC and all PPGF-ECCs. Notably, the MOE values of all PPGF-ECCs exceed that of PC. Among the PPGF-ECCs, the MOE of 1% PPGF-ECC stands out as the highest.



(a)



(b)

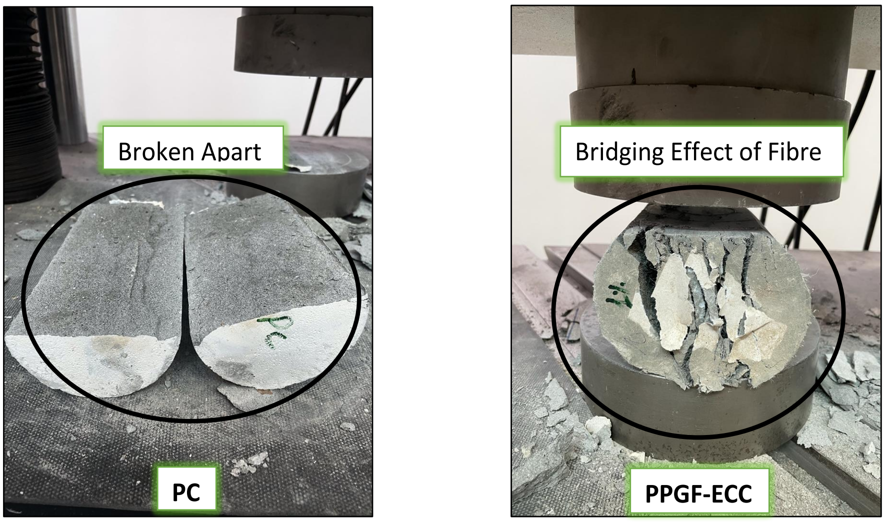
Figure 4.1: Compressive Behaviour: (a) Tested Specimen, (b) Compressive stress strain curve.

This might be attributed to the presence of the optimum fiber content required for achieving optimal compressive strength [98]. Figure 4.1 (a) illustrates the typical compression failures of both PC and PPGF-ECCs.

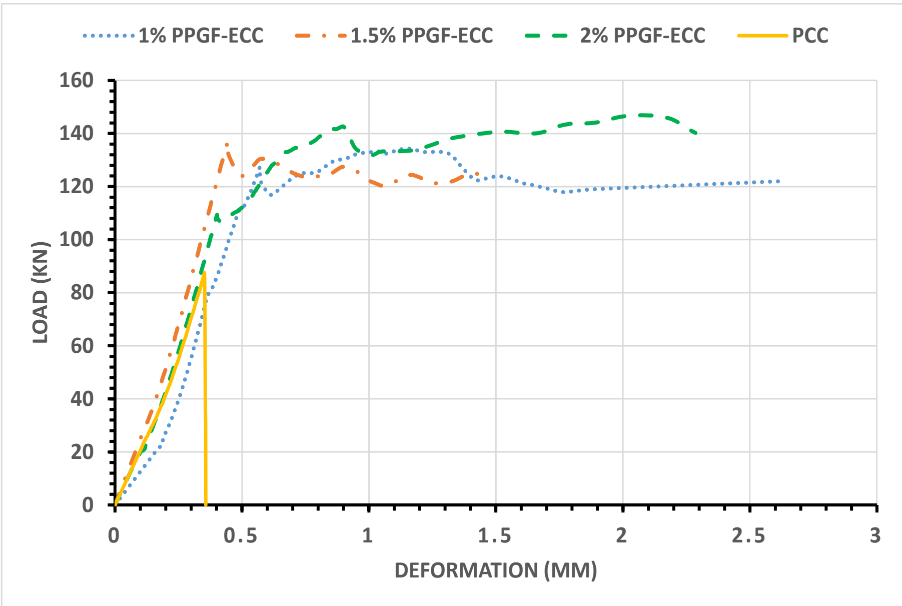
Table 4.2 presents the values of compressive pre-crack absorbed energy (CE1), compressive post-crack absorbed energy (CE2), compressive total absorbed energy (CTE), and compression toughness index (CTI). A noticeable increase is observed in the values of CE1 for 1% PPGF-ECC, 1.5% PPGF-ECC, and 2% PPGF-ECC, with increments of 84.7%, 74%, and 48.8%, respectively, in comparison to PC. In contrast, the corresponding CE2 values exhibit even greater increases, rising by 120%, 123%, and 124% compared to PC. The CTI values for all PPGF-ECCs exceed those of PC. This increase could potentially be attributed to the presence of hybrid synthetic polymers, such as polypropylene and glass fibers. Notably, when subjected to compressive loading, PPGF-ECC samples exhibit diagonal and shear cracks instead of the spalling behavior observed in PC. Among the PPGF-ECCs, both the 2% PPGF-ECC and 1% PPGF-ECC exhibit the highest CTI values. This underscores the positive influence of combining 1% polypropylene and glass fibers on the CTI values. Ranjith et al [99] reported that A fiber content exceeding 1% makes the mix challenging to handle, reducing workability and weakening the fiber-cement bond. ECC with 2% fiber content becomes less dense, more permeable, and exhibits lower compression strength.

4.3.2 Split Tensile Properties

Figure 4.2 (b) illustrates the load-deformation curves for PC, 1% PPGF-ECC, 1.5% PPGF-ECC, and 2% PPGF-ECC. Notably, Figure 4.3b demonstrates that the 2% PPGF-ECC exhibits the highest load-carrying capacity. This enhanced load-carrying capacity can be attributed to the bridging effect of both polypropylene (PP) and glass (G) fibers present in PPGF-ECCs. The incorporation of PP fiber in cement composite significantly enhance the split tensile strength [54].



(A)



(B)

FIGURE 4.2: Split Tensile Behaviour: (a) Tested Specimen, (b) Split Tensile load-deformation curve.

In the splitting tensile properties section of Table 4.2, values for Splitting Tensile Strength (STS), Splitting Tensile Pre-crack Absorbed Energy (SE1), Splitting Tensile Post-crack Absorbed Energy (SE2), Splitting Tensile Total Absorbed Energy (STE), and Splitting Tensile Toughness Index (STI) are provided.

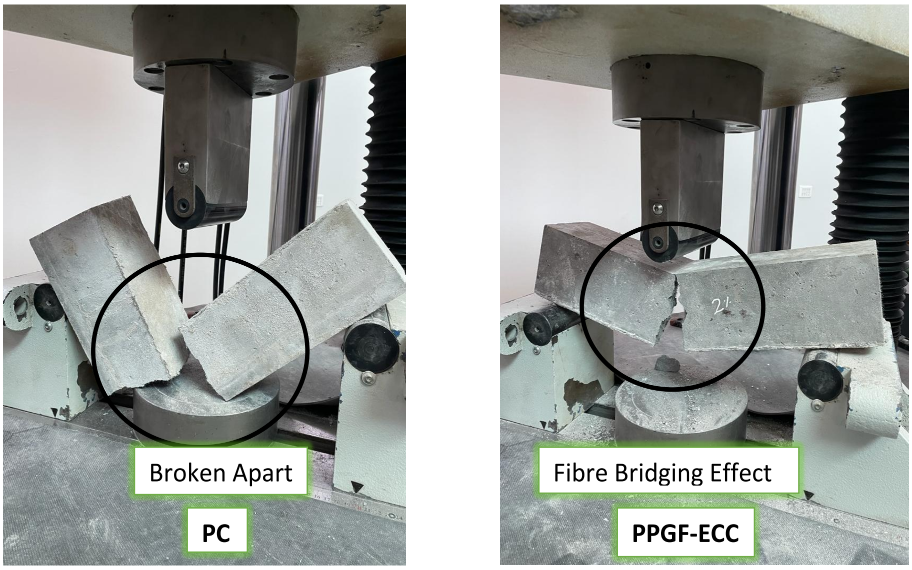
The Splitting Tensile Strength (STS) experiences increases of 45%, 56%, and 63% compared to PC. Remarkably, the 2% PPGF-ECC records the highest STS value, possibly due to an optimal volume percentage of polypropylene and glass fibers. With the increase in fiber content the (STS) increase, similar trend is also reported by Elmoaty et al [100] from low to higher fiber content. The collective STS enhancement in all PPGF-ECCs is attributed to the fiber bridging effect. In terms of Splitting Tensile Pre-crack Absorbed Energy (SE1), the 2% PPGF-ECC exhibits a 79% increase in comparison to PC. PC shows minimal splitting tensile post-crack energy due to its tendency to break into two pieces under peak loading. Synthetic fibers content increase have enhanced the splitting tensile strenegth and toughness of ECC [101].

Conversely, PPGF-ECCs demonstrate post-crack absorbed energies owing to the presence of synthetic polymers (PP and G fibers) within the concrete [102] [103]. This suggests that PPGF-ECCs can endure slightly longer under tensile loading compared to PC. The fibers in the concrete act as crack arrestors, hindering crack propagation. For the PPGF-ECCs, the 1% variant has higher pre-crack energy, while the 2% variant has more post-crack energy than PC. This difference is attributed to the optimal fiber content—6mm polypropylene and 6mm glass fibers—which serve as crack arrestors. Consequently, the 1.5% PPGF-ECC exhibits higher absorbed energy due to this balance. Notably, the Toughness Indexes of 1% PPGF-ECC, 1.5% PPGF-ECC, and 2% PPGF-ECC exceed those of PC. Figure 4.2 (a) showcases the characteristic splitting tensile failures of both PC and PPGF-ECCs. The highest toughness index is exhibited by PPGF-ECCs, attributed to their maximum pre-crack and post-crack energies. This outcome is likely due to the presence of polypropylene fibers and glass fibers, which effectively arrest cracks following tensile loading.

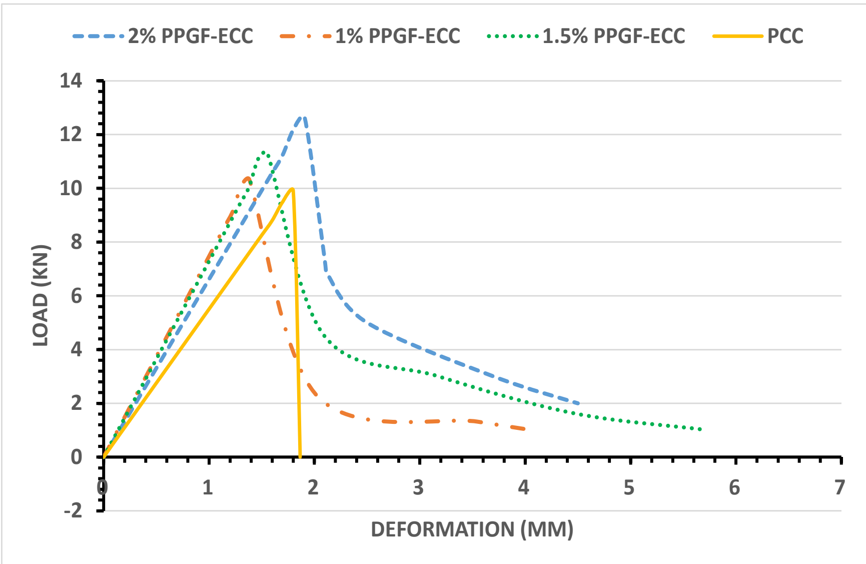
4.3.3 Flexural Properties

Figure 4.5 displays the load-deformation curves for PC, 1% PPGF-ECC, 1.5% PPGF-ECC, and 2% PPGF-ECC. Verma et al [104] and sismal et al [105] denoted similar flexural graphical behaviour of ECC. Notably, in this study, a loading rate of 1 MPa/min is employed, as recommended ASTM standard C78 loading rate of flexural strength test. Remarkably, Figure 4.5 highlights that the 2% PPGF-ECC bears the maximum load due to its robust resistance to flexural loading. This effect can be attributed to the bridging impact of polypropylene (PP) and glass (G) fibers, resulting in the PPGF-ECCs' enhanced load-carrying capacity. Ali et al [106] has reported increase in flexural strength and toughness with increase in glass fiber content. In the "Flexural Properties" section of Table 4.2, values for Flexural Strength (F-S), Flexural Pre-crack Absorbed Energy (FE1), Flexural Post-crack Absorbed Energy (FE2), Flexural Total Absorbed Energy (FTE), and Flexural Toughness Index (FTI) are provided. The Flexural Strength (F-S) experiences increments of 27.4%, 4.2%, and 14.2% compared to PC. Remarkably, the 2% PPGF-ECC attains the highest F-S value, possibly due to an optimal fiber content percentage. Zhang et al [96] and Nili et al [107] reported similar trend of flexural strength with increase in PP fiber content. The collective F-S enhancement across all PPGF-ECCs is attributed to the bridging effect of the fibers. In terms of Flexural Pre-crack Absorbed Energy (FE1), the 1% PPGF-ECC exhibits a 35% increase compared to PC. PC exhibits no flexural post-crack energy, as it breaks into two pieces under peak loading.

In contrast, PPGF-ECCs showcase post-crack absorbed energies owing to the presence of polymer PP and G fibers within the concrete. This suggests that PPGF-ECCs can endure slightly longer under flexural loading than PC, as the fibers act as crack arrestors, resisting crack propagation. Elmoaty et al [100] has reported significant increase in flexural strength and toughness due to increase in fiber content. Kamal et al [108] developed ecc with increase in flexural strength with increase in fiber content.



(a)



(b)

FIGURE 4.3: Flexural Behaviour: (a) Tested Specimen, (b) Flexural load-deformation curve.

TABLE 4.2: PC and PPGF-ECC Mechanical Properties

Specimens	**Compressive Strength**						**Split Tensile**					**Flexural Strength**					
	MOE (GPa)	**C-S (MPa)**	**CE1**	**CE2**	**CTE (MJ/m^3)**	**CTI**	**STS (MPa)**	**SE1**	**SE2**	**STE (MJ/m^3)**	**STI**	**F-S (MPa)**	δ_o **(mm)**	**FE1**	**FE2**	**FTE (MJ/m^3)**	**FTI**
PCC	26 ± 1.3	31 ± 0.8	0.306 ± 0.003	0.060 ± 0.001	0.366 ± 0.05	1.2 ± 0.03	1.8 ± 0.2	19.4 ± 1.1	0 ± 0	19.4 ± 0.2	1	5.9 ± 0.4	1.9 ± 0.5	8.91 ± 0.12	0.32 ± 0.02	9.24 ± 0.31	1
1% PPGF-ECC	35 ± 0.7	56 ± 0.8	0.565 ± 0.004	0.288 ± 0.001	0.854 ± 0.005	1.5 ± 0.05	2.6 ± 0.3	37.7 ± 1.1	8.87 ± 0.01	46.5 ± 1.11	1.23 ± 0.0	6.2 ± 0.2	4 ± 0.4	7.13 ± 0.13	7.32 ± 0.0	14.4 ± 0.13	2 ± 0.0
1.5% PPGF-ECC	32 ± 0.3	46 ± 0.2	0.532 ± 0.001	0.254 ± 0.001	0.787 ± 0.001	1.4 ± 0.06	2.8 ± 0.4	33.6 ± 0.92	18 ± 1.4	52 ± 2.3	1.54 ± 0.05	6.8 ± 0.2	5.7 ± 0.23	8.78 ± 0.06	12.9 ± 0.06	21.7 ± 0.03	2.4 ± 0.01
2% PPGF-ECC	32 ± 0.7	46.5 ± 0.4	0.456 ± 0.004	0.243 ± 0.001	0.699 ± 0.002	1.53 ± 0.04	2.9 ± 0.4	23.6 ± 1.5	21.2 ± 0.96	44.9 ± 2.5	1.89 ± 0.04	7.6 ± 0.2	5 ± 0.5	12.04 ± 0.13	12.5 ± 0.09	24.5 ± 0.21	2.1 ± 0.02

The Toughness Indexes of 1% PPGF-ECC, 1.5% PPGF-ECC, and 2% PPGF-ECC surpass those of PC. The 2% PPGF-ECC claims the highest toughness index due to its superior pre-crack and post-crack energies. In traditional concrete, the utilization of PP fibers enhances compressive strength, splitting tensile strength, and flexural strength [54]. This result is potentially linked to the presence of optimal fiber content, which effectively arrests cracks after flexural loading better than 1% PPGF-ECC, 1.5% PPGF-ECC, and PC. Throughout the test, the loading rate remains constant. As deflection alters, the load increases. Notably, in regions where strong bridging effects and fiber-matrix bonding exist, the sample bears a higher load, resulting in delayed crack propagation. Figure 4.6 depicts the characteristic flexural failures of both PC and PPGF-ECC.

4.4 Mass Loss, Water Absorption, and Linear Shrinkage

Liquid transportation through capillary action is quantified as water absorption, which is computed by dividing the mass of absorbed water by the specimen's mass after oven drying, following the ASTM standard C642-13. The water absorption values for PC and all PPGF-ECCs are provided in Table 4.3. It's noteworthy that the 2% PPGF-ECC exhibits the highest water absorption, while PC showcases the lowest water absorption value. Synthetic fibers like polypropylene (PP) fibers have an inherent tendency to absorb water. Consequently, the water absorption of all PPGF-ECCs surpasses that of PC. Moreover, it's evident that as the percentage content of PP and glass (G) fibers increases, the water absorption of PPGF-ECC specimens escalates. The 2% PPGF-ECC employs the maximum fiber content combination, incorporating 1% PP and 1% G fibers. This results in the highest water absorption, surpassing PC's water absorption by almost double.

Table 4.3 presents the linear shrinkage values of both PC and PPGF-ECC. Notably, there is an overall reduction in the linear shrinkage values of PPGF-ECCs when compared to PC. Additionally, an interesting observation is that with the increase in fiber percentage from 1% PPGF-ECC to 2% PPGF-ECC, the linear shrinkage experiences a decrease. This effect is particularly pronounced when transitioning from 1% PPGF-ECC to 2% PPGF-ECC, with the increment in polypropylene (PP) and glass (G) fiber percentages contributing significantly to the reduction in linear shrinkage values. This reduction can be attributed to the presence of a higher fiber percentage. It can be inferred that the incorporation of synthetic fibers, such as the combination of PP and G fibers, may enhance the concrete's resistance to cracking, ultimately diminishing its susceptibility to linear shrinkage.

The Table 4.3 provides insights into the mass loss of PPGF-ECC. Notably, the highest mass loss occurs at the temperature of 100°C, whereas PC exhibits the least mass loss, and PPGF-ECC experiences the most substantial mass loss. Notably, as the fiber content escalates from 1% PPGF-ECC to 2% PPGF-ECC, the mass loss also increases. An intriguing observation is the positive impact of incorporating 2% polypropylene (PP) and glass (G) fibers in combination, which influences mass loss. Additionally, the mass loss at 50°C is approximately 33% lower compared to the mass loss at 100°C. This discrepancy can be attributed to the gradual and continuous heating process required to reach the temperature of 100°C.

Table 4.3: PC and PPGF-ECC Water Absorption, Mass Loss and Linear Shrinkage

			ML Temperatures		
Specimens	**WA (%)**	**LS(%)**	**50°C**	**75°C**	**100°C**
PCC	1.5	2.4	-0.003	-0.004	-0.005
1% PPGF-ECC	2.1	2.1	-0.016	-0.017	-0.019
1.5% PPGF-ECC	2.5	1.9	-0.014	-0.018	-0.022
2% PPGF-ECC	2.8	1.8	-0.019	-0.024	-0.028

4.5 Modernized Testing

4.5.1 SEM Analysis

SEM analysis was employed to investigate the damage morphology of fibers and the matrix at the tensile fracture section, providing insights into ECC/BC microstructures. Therefore SEM of broken specimens in flexure was conducted in this study. Fig 4.4 presents the sem images of the PPGF-ECC composites. Fiber pull-out signifies friction between the fiber and matrix, while fiber rupture indicates an even stronger friction at this interface [81]. Glass fibers experienced pullout failure, whereas PP fibers exhibited both pullout and rupture failures. PP fiber rupture suggested effective utilization of its strength in the ultra-high strength matrix. Glass fibers, with their higher modulus and tensile strength compared to PP fibers, only exhibited pullout failure. SEM images reveal that Glass fibers exclusively undergo a pull-out phenomenon from the matrix, whereas PP fibers exhibit both pull-out and surface delamination. Both Glass and PP fiber surfaces are coated with hydration products, indicating a robust fiber/matrix interfacial bond. The paste's microstructure featured extensive layers of amorphous calcium hydroxide (CH) and crystals of calcium silicate hydrate (C-S-H), with ettringite (E) needles visible within the pores. The dense microstructures of the reinforced matrix, combined with high-strength mixtures, typically yield a robust fiber/matrix interfacial bond. In such instances, small matrix debris is frequently observed on the fiber during the pull-out process due to the fiber's relatively higher stiffness compared to the matrix. However, polymer-based fibers, which tend to have lower stiffness, may display surface scratches in addition to attached debris [8]. Images reveal evidence of friction on the surface of PP fibers, indicating that the dense PPGF-ECC matrix created a robust bond and friction interaction between the fibers and the matrix. This strong fiber/matrix bond resulted in the rupture of certain PP fibers on the failure surface. Both pulled-out and ruptured PP fibers can be observed, with the former contributing more favorably to the tensile properties of ECC compared to the latter.

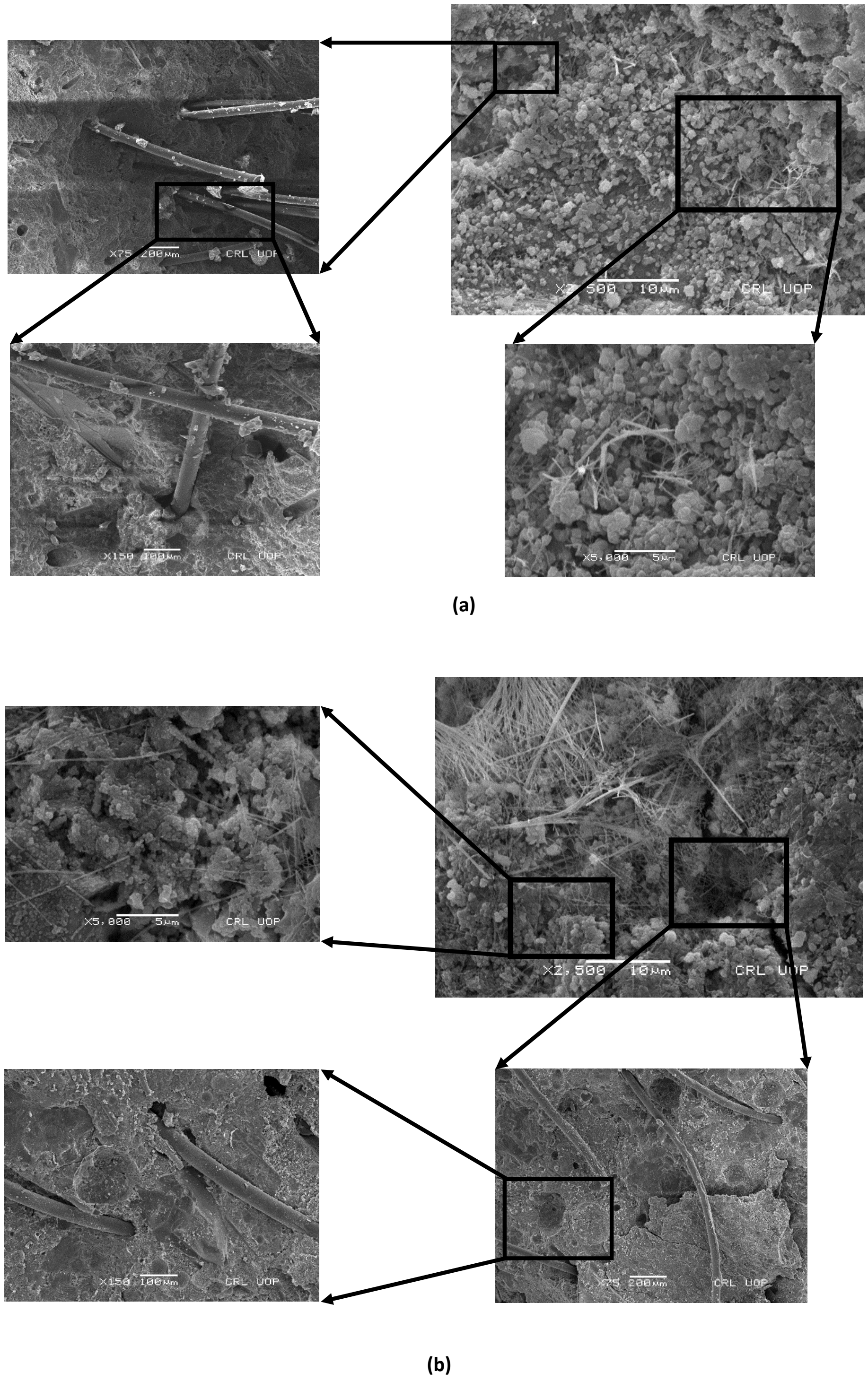


Figure 4.4: SEM Images. (a) 2% PPGF-ECC Images, (b) 1.5% PPGF-ECC Images.

The rupture of PP fibers can significantly restrict the tensile strain capacity of

ECC, primarily due to the superior interfacial properties and large inclination angles of the fibers [79]. On the other hand, the combination of pull-out and rupture failures in PP fibers suggests their effective bridging of cracks in ECC during tensile loading.

4.6 Summary

Within this chapter, an array of properties concerning PC and PPGF-ECC is evaluated. Employing a mix design ratio of 1:0.8:1.2 and a water-to-cement (W/C) ratio of 0.55 for PC and 0.30 for all PPGF-ECC variants, dynamic properties, mechanical attributes, water absorption, mass loss, and linear shrinkage properties are assessed. By augmenting the content of polypropylene (PP) and glass (G) fibers, the dynamic modulus of rigidity experiences enhancement. Furthermore, the incorporation of PP and G fibers results in improvements across parameters such as splitting tensile strength, splitting tensile toughness, flexural strength, flexural toughness, and the capacity to absorb pre-crack and post-crack energy. Notably, compressive toughness is elevated in tandem with increasing compressive strength. The water absorption of PPGF-ECCs is amplified as fiber content is escalated. Intriguingly, linear shrinkage exhibits an inverse relationship with the augmentation of fiber content. Correspondingly, an increase in fiber content percentage leads to a more pronounced observation of mass loss. Upon scrutinizing the fractured surfaces of specimens subjected to mechanical tests, it becomes evident that hybrid synthetic fibers establish robust bonding with the surrounding matrix. The phenomena of fiber pullout and fiber breakage also manifest.

Chapter 5

Discussion and Guidelines for Practical Implementation

5.1 Background

The specimens that underwent testing yielded quantifiable results illustrating the impact of PP and G fibers, as well as fly ash, cement, and silica sand, on the characteristics of the ECC/BC composite. Graphs depicting stress-strain relationships, load deflection, and load deformation were employed to visually convey the influence of the combined content of hybrid PP and G fibers on the mechanical properties of the composite. The data extracted from both dynamic and mechanical testing was subsequently utilized to determine the optimal percentage composition of PP and G fibers. Moreover, this research engages in comprehensive discussions concerning the practical application of the findings. Additionally, recommendations for the real-world utilization of ECC/BC produced using locally available materials are presented within this chapter.

5.2 Comparison of Different Properties from Previous Studies.

The key characteristics of ECC revolve around its exceptional tensile ductility, high strain capacity under tension, and notably elevated flexural strength, often ranging from 2 to 3 times that of conventional concrete [79]. The remarkable tensile ductility of ECC arises from a process involving the emergence of multiple steady-state micro-cracks, referred to as pseudo strain-hardening [80]. This effect arises in these novel composites through precise interface optimization between fibers and matrix, coupled with the fracture traits of the cementitious matrix. Additionally, the heightened tensile ductility of optimal ECC materials directly contributes to increased flexural strength. This inherent ductility prompts notable stress redistribution under flexural loads, ultimately enhancing load carrying capacity.

Nexus to above material characteristics due to composition, fiber/matrix interface and fiber/matrix inter-facial bonding are responsible for achieving the ideal ECC properties [48]. The fiber characteristics vary therefore ECC produced with different fibers will exhibit ideal to low quality of ECC properties. Based on the above experience comparison of different properties from previous study is carried out and presented in Table 2.1 of chap 2. The properties taken into consideration consists of fracture pattern, Composite behaviour, Compressive strength, Flexural strength, Strain/Deformation. The range of properties vary from high to low. High flexural/compressive strength, High strain/deformation with Strain hardening behaviour and multiple steady micro cracks exhibits ideal ECC properties, while moderate-low flexural/compressive strength, moderate deformation, with brittle failure and single large crack exhibits FRC properties. Zhu et al [88] and Yu et al [12] has produced ECC with Multiple steady cracks formation, strain hardening behaviour, high strength and high strain percentage due to which it is characterized as ideal ECC/BC. Xu et al [77] and Choi et al [17] has produced ECC with Multiple spaced cracks. pseudo ductile behaviour, high strength and moderate strain percentage due to which it is characterize as Good ECC composite. Fahad et al [42] and Deng et al [13] material exhibited single spaced cracks

TABLE 5.1: Experimental Results of Properties for Characterization of ECC/BC, HPFRCC/BC

S.No	**Composite**	**Fiber**	**Fracture Pattern**	**Composite Behaviour**	**Compressive Strength (MPa)**	**Tensile Strength (MPa)**	**Flexural Strength (MPa)**	**Deformation %**
1.	1% PPGF-ECC	PP, GF	Single crack	Pseudo Ductile	56	2.6	6.2	4
2.	1.5% PPGF-ECC	PP, GF	Single crack	Pseudo Ductile	46	2.8	6.8	5.7
3.	2% PPGF-ECC	PP, GF	Single crack	Pseudo Ductile	46.5	2.9	7.6	5

with pseudo ductile behaviour. moderate strength and moderate deformation percentage due to which composite is characterized as acceptable ECC. HPFRCC was developed by Hungria et al [69] and Khan et al [83] with signle spaced cracks, pesudo ductile behaviour, moderate strength and modertae deformation. While Zhang et al [48] composed FRC composite with single crcaks, low ductility, moderate strength and low deformation. Data of experimental results achived in this study is provided in table 5.1. The data is used for characterization of ECC/BC, which shall be studied in light of literature review conducted in table 2.1 in chap 2 for characterization of the composite. In the comparison of the properties defined for ECC the present composite have moderate to high strength and deformation with pesudo ductile behaviour and single crack formation which places this composite in the category of acceptable ECC/BC or HPFRCC/BC.

5.3 Implementing this Research in Practical Situations.

In the realm of civil engineering structures, the concrete employed undergoes a variety of simultaneous loads, encompassing both mechanical and dynamic pressures. These loads contribute to the emergence of fractures on both the external and internal facets of the concrete. Additional factors leading to these cracks include heightened water absorption rates, elevated linear shrinkage values, and reduced tensile strength during the tension phase of the concrete. On rigid pavements, surface cracks manifest due to diminished flexural strength and non-uniform settling. The mitigation of these cracks can be achieved by bolstering the flexural potency of the concrete. Another noteworthy vulnerability of concrete is the occurrence of spalling [11]. This phenomenon is triggered when concrete is subjected to heightened temperatures.

Marine and coastal concrete structures facing typhoons, earthquakes, and tsunamis endure diverse loads. Engineered Cementitious Composites (ECC/BC) offer promise, replacing or reinforcing traditional concrete in critical parts like beam-column joints and functionally-graded components, significantly enhancing structural strength [73]. Effective utilization of ECC has the potential to enhance both the load-carrying capacity and ductility of assembled beam-column joints subjected to cyclic loads. Substituting traditional concrete with ECC at these joints resulted in a notable 17% increase in load-carrying capacity and an impressive 220% improvement in ductility [84]. Unlike standard RC beam-column joints, the composite RC/ECC joint displayed increased load capacity, ductility, and energy dissipation. Introducing ECC in the joint area without stirrups led to notable gains in these aspects, credited to ECC's strong shear capacity and ductility. Substituting concrete with ECC in joints enhances seismic performance, even with reduced shear reinforcement, compared to well-designed RC members [64]. Beyond ductile behavior in quasi-static tension and flexural tests, ECC retained its ductility under high strain rates in monolithic and composite slabs subjected to impact loads. While RC slabs suffered perforation and spalling, ECC slabs mitigated local failures, preserving structural integrity. The ECC slabs displayed extensive global deformation, ultimately failing with a central crack, illustrating ductile behavior throughout the response [5]. The fatigue performance under flexural stress of ECC/BC outperformed that of standard concrete, suggesting potential for extended pavement lifespan and reduced thickness requirements [109]. This characteristic has practical implications, preventing brittle failure and enhancing concrete pavement performance.

This study investigates the impact of incorporating hybrid synthetic fibers with different fiber content in composites. The specimens containing 1% PPGF-ECC demonstrated enhanced behavior under compressive loads, making them suitable for use in compression members such as architectural or structural columns. These columns find application in multi-story structures, up to twenty stories, where robust strength capacity is essential. Among various PPGF-ECCs, the 1% PPGF-ECC demonstrates notably enhanced properties. Its superior performance in splitting tensile and flexural loading renders it suitable for incorporation in slabs and beams. The efficacy of 1% PPGF-ECC extends to rigid pavements, which are meticulously designed considering concrete's flexural strength and modulus of

TABLE 5.2: Optimization of fiber content in PPGF-ECCs

Composite	**Compression**				**Split**	**Tensile**		**Flexural**			**Dynamic**	
Type	**MOE (GPa)**	**C-S (MPa)**	**CTE (MJ/m^3)**	**CTI**	**STS (MPa)**	**STE (MJ/m^3)**	**STI**	**F-S (MPa)**	**FTE (MJ/m^3)**	**FTI**	**RD (GPa)**	ζ%
PCC	26.42± 1.3	31 ± 0.8	0.366± 0.05	1.2 ± 0.03	1.8 ± 0.2	19.6 ± 1.1	1	5.9 ± 0.4	9.24 ± 0.31	1	1.5 ± 0.03	1 ± 0.01
PPGF-ECC with minimum values	32 ± 0.7 (2% PPGF)	46 ± 0.8 (1.5% PPGF)	0.0699± 0.02 (2% PPGF)	1.48 ± 0.04 (1.5% PPGF)	2.6 ± 0.3 (1% PPGF)	45 ± 1.5 (2% PPGF)	1.23 ± 0.05 (1% PPGF)	6.2 ± 0.2 (1% PPGF)	14.4 ± 0.21 (1% PPGF)	2.01 ± 0.2 (1% PPGF)	3.1 ± 0.3 (1% PPGF)	1.3 ± 0.05 (1% PPGF)
PPGF-ECC with maximium values	35 ± 0.7 (1% PPGF)	56 ± 0.8 (1% PPGF)	0.854± 0.001 (1% PPGF)	1.53 ± 0.005 (2% PPGF)	2.9 ± 0.4 (2% PPGF)	52 ± 2.3 (1.5% PPGF)	1.89 ± 0.02 (2% PPGF)	7.6 ± 0.2 (2% PPGF)	24.5 ± 0.4 (2% PPGF)	2.4 ± 0.03 (1.5% PPGF)	4.1 ± 0.2 (2% PPGF)	1.6 ± 0.04 (2% PPGF)

TABLE 5.3: Recommended Composites to industry for Structural Elements

Recommended												
1. For Specific Property												
a. From Strength Point of View	1%	PPGF			2%	PPGF		2%	PPGF		1%	PPGF
	35	56	0.854	1.5	2.9	44.9	1.89	7.6	24.1	2.4	3.1	1.3
b. From Toughness Point of View	1%	PPGF			1.5%	PPGF		2%	PPGF		2%	PPGF
	35	56	0.854	1.5	2.8	52	1.54	7.6	24.5	2.1		1.6
2. For Specific Application												
a. 1% PPGF-ECC for Column/Compression Members	35	56	0.854	1.5	2.6	46.5	1.23	6.2	14.4	2	3.1	1.3

b. 2% PPGF-ECC for slabs and beams	32	46.5	0.699	1.53	2.9	44.9	1.89	7.6	24.5	2.1	4.1	1.62
c. 1.5% PPGF-ECC for foundations	32.1	46	0.787	1.48	2.8	52	1.54	6.8	24.7	2.4	3.8	1.45
d. 2% PPGF-ECC for rigid pavements	32	46.5	0.699	1.53	2.9	44.9	1.89	7.6	24.5	2.1	4.1	1.62

elasticity. This variant proves fitting for rigid pavements, showcasing improved modulus of rupture and modulus of elasticity—critical determinants of stability and durability. While possessing commendable compressive strength, 1% PPGF-ECC exhibits superior energy absorption and toughness within the realm of all PPGF-ECC variations. Employing these hybrid fibers as eco-friendly construction materials could serve as a stride toward sustainable development.

5.4 Summary

After determining the ideal fiber content percentage in mixtures of PP and G fibers, recommendations are provided based on strength and toughness aspects. Practical usage suggestions for PPGF-ECC across various structural elements like columns, beams, and slabs are outlined. The blend exhibiting superior properties is endorsed for utilization in rigid pavements.

Chapter 6

Conclusion and Recommendations

6.1 Conclusions

This study aims to develop flexible engineered cementitious composites (BC/ECC) using local materials and explore their mechanical and dynamic properties. BC/ECCs with varying fiber content (1%, 1.5%, and 2%) of PP and G fibers were created. Mechanical properties (strength, energy absorption, toughness) under different loadings, dynamic properties (Poisson's ratio, modulus of rigidity, damping ratio), and additional factors (linear shrinkage, mass loss) were investigated. The study assesses PPGF-ECC's structural potential for civil engineering structures. In summary, it focuses on developing and evaluating versatile BC/ECC materials for potential engineering applications.

- Findings show higher water absorption in 2% PPGF-ECC (87% increase) compared to plain concrete (PC). Other composites, like 1% PPGF-ECC and 1.5% PPGF-ECC, also exhibit increased rates (40% and 67%, respectively) compared to PC, which has the lowest rate (46% less than 2% PPGF-ECC).

- Mechanical properties of PPGF-ECC exhibited notable improvements compared to conventional plain concrete (PC). These enhancements encompassed increased strength, energy absorption before and after the peak, and a higher toughness index, demonstrating the superior performance of PPGF-ECC.

  - The study indicates that 1% PPGF-ECC boasts the highest compressive strength, exceeding PC by 78%. It also exhibits the highest CTE, surpassing PC by 133%. Meanwhile, 1.5% PPGF-ECC records a significant 173% increase in CTI compared to PC. The combination of PP and GF at 1.5% volume achieves maximum post-cracking energy. However, 1.5% PPGF-ECC shows the lowest compressive strength.
  - The 2% PPGF-ECC achieved the highest Split Tensile Strength (STS), increasing by 63% compared to PC. Likewise, 1% PPGF-ECC and 1.5% PPGF-ECC displayed substantial STS improvements of 45% and 56%, respectively, over PC. Additionally, Split Tensile Energy (STE) increased for all PPGF-ECC variants compared to PC
  - The study shows that PPGF-ECC composites outperform PC in flexural strength, with increases of 27%, 14%, and 4% for 2%, 1.5%, and 1% PPGF-ECC, respectively. The 2% PPGF-ECC achieves a peak toughness index at 139%, while all other specimens also exhibit improved flexural strength compared to PC. This suggests that the optimal blend of PP and G fibers in 2% PPGF-ECC (PP1%-G1%) contributes to its enhanced flexural performance.

- Due to the bridging effect of hybrid fibers, the concrete effectively prevented sudden failure, resulting in the presence of post-crack energy across all PPGF-ECCs, in contrast to PC.

- Hybrid synthetic fibers improve dynamic load resistance, enhancing damping ratio (Rd) and dynamic modulus (Ed) in PPGF-ECC cylinders and beamlets.

- SEM analysis of destructive samples from mechanical tests reveals intact bond between synthetic hybrid fibers and concrete. G fibers had pull-out, while PP fibers showed breakage, with evidence of fiber bridging in fractured samples.
- Recommend 1% PPGF-ECC for compressive members and pavements; opt for 2% PPGF-ECC in beams, slabs, rigid pavements, and structures prone to dynamic loads for improved properties.

This study identifies 1% PPGF-ECC (0.5%PP-0.5%G) and 2% PPGF-ECC (1%PP-1%G) as superior composites. These are recommended for countering spalling, cracking, flexural stress, and dynamic loads, with suitable properties for rigid pavements. Synthetic fibers emerge as a practical and sustainable construction material option.

6.2 Future Recommendations

The synergistic impact of incorporating supplementary cementitious materials with varying fiber contents of PP and G fibers exhibits the potential to greatly enhance both the dynamic and mechanical properties of concrete. To delve further into the behavior of PPGF-ECC/BC, the following recommendations should be considered for future research:

- Conduct experiments with different fiber diameters, filler combinations, supplementary cementitious materials, or dual admixture usage to assess combined effects.
- Validate experimental outcomes through analytical modeling.
- Fracture energies of bendable concrete.
- Perform a Life Cycle Cost Analysis (LCCA) for bendable composite materials, encompassing processing and construction aspects to explore the economic viability.

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