Optimization of Braided Structures for Civil Engineering Application

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CHAPTER 1
INTRODUCTION

1.1 Introduction to Rebars

Reinforcement bars, also known as rebar or reinforcing steel, are steel bars that are commonly used in reinforced concrete structures to provide strength and durability. Reinforced concrete is a composite material that combines the strength of concrete with the tensile strength of steel. Rebars are typically made of carbon steel and have a ribbed surface to provide better bonding with the surrounding concrete. The ribs on the surface of the bars increase the frictional resistance between the steel and concrete, preventing slippage and ensuring better load transfer between the two materials[1], [2]. The main purpose of reinforcement bars is to withstand the forces applied to the concrete structure. While concrete is strong in compression, it is weak in tension. By incorporating reinforcement bars into the concrete, the tensile forces are transferred to the steel bars, which can handle the tension effectively. This combination of concrete and steel creates a structural system that can withstand various loads and environmental conditions. Conventional reinforcement bars have several limitations that can affect the performance and durability of reinforced concrete structures. Some of these limitations include [2], [3][4]:

1. Corrosion: One of the most significant limitations of conventional rebar is its susceptibility to corrosion. When exposed to moisture and environments, such as chloride ions from saltwater or carbon dioxide from air pollution, the steel bars can corrode. Corrosion leads to the formation of rust, which expands and weakens the bars, ultimately compromising the structural integrity of the concrete.

2. Weight and Handling: Conventional rebars are heavy and can be challenging to handle, transport, and install on construction sites. The weight and bulkiness of the bars make construction processes more labor-intensive and time-consuming.

3. Design Limitations: The use of conventional rebar can impose certain design limitations. For example, the size and shape of the rebar can limit the complexity of concrete structures and architectural designs. It can be challenging to incorporate rebar into intricate or curved shapes, leading to design constraints.

4. Thermal Expansion: Steel has a higher coefficient of thermal expansion than concrete. Temperature variations can lead to differential expansion and contraction between the steel rebar and the concrete, causing internal stresses and potential cracking within the structure.

5. Electromagnetic Interference: Conventional rebar can create electromagnetic interference (EMI) that can affect electronic devices and systems. In sensitive environments, such as hospitals, laboratories, or data centres, the use of rebar may require additional measures to mitigate EMI.

Alternative reinforcement methods and materials have been developed to navigate around some of these constraints. One of the best alternatives to it is fiber-reinforced polymers (FRP). Rebar made of fibre-reinforced polymer (FRP) has several advantages over traditional steel rebar, overcoming some of the drawbacks associated with using steel reinforcement. Here are some advantages of using FRP rebar[5]–[7]:

1. Corrosion Resistance: FRP rebars are non-metallic and do not corrode like steel rebar. This makes them highly resistant to deterioration caused by moisture, chloride ions, and other aggressive chemicals. As a result, structures reinforced with FRP rebar have a longer service life and require less maintenance and repair.

2. Light Weight: FRP rebars are significantly lighter than steel rebars, typically weighing about one-fourth the weight of steel for the same strength. The lightweight nature of FRP rebar simplifies handling, transportation, and installation on construction sites. It can also reduce the dead load of the structure, leading to potential cost savings in the design and construction of the supporting elements.

3. High Strength-to-Weight Ratio: FRP rebars have a high strength-to-weight ratio, meaning they are stronger than steel rebars of the same weight. This allows for the design of more slender and lightweight structures without compromising strength and safety.

4. Non-Magnetic and Non-Conductive: FRP rebar are non-magnetic and non-conductive, which makes them suitable for applications in sensitive environments, such as medical facilities or areas with electromagnetic interference (EMI) concerns. They do not interfere with electronic devices, and their non-conductive nature can enhance electrical safety.

5. Thermal Insulation: FRP rebar has lower thermal conductivity compared to steel rebar.

This property helps in reducing thermal bridging and can contribute to improved energy efficiency in buildings and structures.

6. Design Flexibility: FRP rebar can be easily shaped and customized to meet specific design requirements. They can be manufactured in various sizes, shapes, and configurations, enabling greater flexibility in architectural and structural design. FRP rebar can also be bent on-site, allowing for easier installation around corners and curved elements.

1.2 Manufacturing Process

FRP (fibre-reinforced polymer) rebar is made through a manufacturing process that combines fibres and a polymer matrix. The first step in the manufacturing process is the selection of fibers. The choice of fiber depends on the desired mechanical properties, such as strength, stiffness, and corrosion resistance. The most commonly used fibers in FRP rebar are glass fibers, carbon fibers, or aramid. The selected fibers are impregnated with a polymer resin. The resin can be epoxy, vinyl ester, or other compatible polymer matrices. The impregnation process ensures that the fibres are thoroughly wetted and evenly distributed within the resin, providing a strong bond between the fibers and the matrix. After impregnation, the fibers are aligned and arranged in a specific pattern to optimize the mechanical properties of the final FRP rebar. The formed FRP rebar are then subjected to a curing process to harden the polymer matrix. The curing can be done at ambient temperature or in a temperature-controlled environment, depending on the resin system used. The curing process allows the resin to crosslink and form a solid and durable structure[8], [9].

1.3 Textile Braiding

It is one of the fabric manufacturing techniques used to create three-dimensional structures by intertwining textile fibres in a particular pattern to form a flexible and strong structure. The resulting braided textile can be used for various applications, ranging from clothing and accessories to technical and industrial products. Textile braiding offers several advantages, including high flexibility, strength, and elasticity. The braided structures can be customized to have different patterns, densities, and thicknesses, making them suitable for various applications[10]. Braided textiles are commonly used in products such as ropes, cords, cables, hoses, shoelaces, and even medical devices like sutures and stents[11]. There is a wide range of engineered textile structures that are created through the process of textile braiding. These products are designed to offer specific performance characteristics and fulfil various technical

requirements.

1.4 Aim of the Study

In the present investigation, an attempt has been made to develop a composite fiber reinforcement bar using the braiding technique with a high-tenacity textile material like basalt, Nylon and polypropylene as reinforcement material and epoxy resin as matrix material. This work covers both fundamental and applied research associated with BCRs and presents possible directions for further development of high-performance composites. Materials selected for the manufacturing of BCR are commercially successful materials used in the field of technical textiles. Products with different materials and diameters have been prepared and evaluated. To provide condensed information, the work has been divided into six chapters which are entirely dedicated to the work.

Chapter 1 gives a brief Introduction of the whole thesis and the type of work carried out. Chapter 2 shows an extensive survey of literature and work carried out by other researchers in this area. Chapter 3 deals with the selection of raw materials and methods used for the production and evaluation of prepared BCR. Chapter 4, contains different observations of all the prepared samples obtained with different fibres and diameters and their possible attributes. Chapter 5, further uses the observed data for a mathematical model which helps in predicting the behavior of the prepared BCR. Chapter 6, gives a concluding remark of the work. At the end, the thesis provides appendices for explanation of abbreviations, symbols, and references.

As different products have been prepared and studied, to have a comprehensive understanding of the work, chapters 3 and 4 have been further divided into different sections

Section I: Deals with the modification of the existing biaxial braiding machine to facilitate an additional third axial yarn which will be introduced at zero degrees, during braiding. Such a braiding machine is known as Tri-axial braiding. Apart from this, the take-up mechanism was also modified to achieve different take-up rates. Thus, modification was carried out in the existing machine and was made versatile for the manufacturing of biaxial as well as triaxial braided products.

Section II: The high-tenacity yarns procured were used as raw material for the manufacturing of triaxial braided ropes. The diameter of the manufactured ropes was increased by incorporating the previous braided rope as a core material in the preparation of the new rope.

This is known as the braid over braid technique.

Section III: This section covers the preparation of composite rods by using the prepared rope of different diameters as a reinforcement material.

Detailed analysis was carried out during different stages of FRP rod manufacturing. The procured yarn was tested for its linear density and tensile properties. The rope prepared from the material was also evaluated for its linear density, braid geometry and tensile properties. The prepared rods were further analyzed for their diameter, fiber volume fraction, and other mechanical properties. The prepared rods were also subjected to the preparation of cemented blocks and beams, for checking the performance of prepared rods inside the cement structure in terms of bonding and flexural strength respectively.

CHAPTER 2
Literature Review

Literature review highlights the evolution of technical textiles, which have gained prominence in various specialized applications over the past few decades, such as protective clothing, medical products, and construction materials. Unlike traditional textiles, technical textiles are designed for their functional properties, utilizing high-performance fibers and specialized manufacturing processes. They are categorized into twelve areas, including agrotech, buildtech, and meditech, each serving distinct purposes. The advantages of technical textiles, such as flexibility, strength, and lightweight nature, position them as viable alternatives to conventional materials like steel and wood in engineering applications. Research in this field focuses on optimizing the performance of these materials through experimental studies, aiming to enhance their adoption in construction and engineering sectors.

Braiding techniques include flat, round, and square braids, each characterized by different patterns and yarn orientations. Braids can be classified into bi-axial and tri-axial structures based on the arrangement of yarns, with tubular, flat, square, and solid braids representing different forms. Key characteristics of braided structures, such as braid angle, number of fiber bundles, fiber orientation, density, and porosity, significantly influence the mechanical properties of braided composites. These properties can be tailored to meet specific application requirements, allowing for a wide range of performance characteristics in composite materials.

Textile composites are materials created by combining fibers, yarns, or fabrics with a matrix, typically a polymer resin. This combination enhances the composite's strength and stiffness while the matrix protects the fibers. Key characteristics of textile composites include:

1. **Strength**: They offer high strength-to-weight ratios, influenced by the reinforcement fibers and matrix type.
2. **Stiffness**: High stiffness makes them suitable for structural applications, with performance depending on reinforcement type and fiber orientation.
3. **Durability**: Essential for applications like wind turbines and sporting goods, durability is determined by the materials used and the manufacturing process.

4. **Fatigue Resistance**: Good fatigue resistance is crucial for cyclic loading applications, such as in aircraft and sports equipment.
5. **Impact Resistance**: They can withstand high-velocity impacts, making them ideal for automotive and ballistic applications.
6. **Customization**: Textile composites can be tailored in terms of reinforcement type, fiber orientation, and matrix material to meet specific application needs.

High-performance textile fibers serve as essential reinforcement materials, significantly improving the mechanical properties of composites. Below, we highlight some of these fibers along with their key performance parameters.

Nylon is a strong, durable synthetic fiber known for its resistance to abrasion, lightweight nature, elasticity, fast drying, and chemical resistance. However, it has drawbacks such as low moisture absorbency, static generation, and sensitivity to sunlight.

Polypropyleneis another lightweight, water-repellent fiber that dries quickly and is durable against abrasion and chemicals. It is commonly used in geotextiles and packaging. Its limitations include low breathability, odor retention, and a low melting point.

Polyester, derived from petroleum, is valued for its strength, durability, wrinkle resistance, quick drying, and shape retention. It is versatile and can be blended with other materials, but it also has low moisture absorbency, can generate static cling, has a lower melting point, and is not biodegradable, raising environmental concerns.

Basalt Fiber**:** Derived from volcanic rock, basalt fiber is an emerging textile option known for its high strength and moderate elasticity, often surpassing steel in specific strength. It is heat resistant, making it suitable for fire protection and industrial applications, and offers good thermal and electrical insulation. Additionally, basalt is eco-friendly due to its natural origin. However, its limited availability and higher cost compared to more established fibers, along with its abrasiveness, can be drawbacks.

Carbon Fiber**:** Composed primarily of carbon atoms, carbon fiber is renowned for its exceptional strength-to-weight ratio and stiffness, making it ideal for high-performance applications. It is corrosion-resistant, has a low coefficient of thermal expansion, and exhibits excellent fatigue resistance and vibration damping properties. Carbon fiber can conduct

electricity, which may require insulation in certain uses. Its modern aesthetic appeal adds to its popularity in consumer goods.

Glass Fiber: Also known as fiberglass, glass fiber is made from fine glass filaments and is valued for its high strength, lightweight nature, and durability. It comes in various types, including E-glass for electrical insulation and S-glass for structural applications. Glass fiber is moisture-resistant, non-flammable, and offers good thermal insulation. Its flexibility allows for diverse applications, and it maintains dimensional stability under various conditions, making it reliable for use in aerospace, automotive, and construction industries.

There is long list of such high-performance textile fibers known for their exceptional properties like Aramid fiber like kevlar&nomex, Metallic fibers, Ceramic fibers, Polyimide fibers etc. fibers each possess unique properties that enhance the performance of textile composites, making them suitable for a wide range of industrial applications.

Matrix Material:

In composite materials, the matrix serves as the continuous phase that surrounds and supports reinforcement fibers, providing shape and protection from environmental damage. The matrix typically consists of polymers, categorized into thermoplastic and thermoset resins.

- Thermoplastic Resins:These polymers can be reshaped upon heating and are known for their toughness, impact resistance, and chemical resistance. Common examples include polyethylene, polypropylene, and nylon, used in various applications like automotive parts and medical devices.

- Thermoset Resins: These undergo an irreversible curing process, resulting in a rigid structure with high thermal stability and superior mechanical properties. Examples include epoxy, polyester, vinyl ester, and phenolic resins, which are ideal for high-performance applications in aerospace, automotive, and construction.

    - Polyester: Used in transportation and construction for its low cost and versatility.
    - Vinyl Ester: Similar to polyester but with excellent chemical resistance, suitable for corrosion-prone applications.

- Phenolic: Known for fire resistance and low emissions, used in high-temperature applications.
- Polyurethane: Tough and impact-resistant, commonly used in automotive components.
- Epoxy: Offers high strength, good adhesion, and chemical resistance, widely used in reinforcing systems.

Braided Composites:

These composites feature braided reinforcement materials, providing a tubular structure that enhances strength and stiffness. The braided design allows for even load distribution, reducing stress concentrations and improving damage tolerance. Braided composites are highly customizable and are used in various industries, including aerospace, automotive, and sporting goods, for applications requiring high strength, durability, and lightweight construction. The combination of matrix materials and braided structures in composites leads to innovative solutions across multiple sectors, leveraging their unique properties for enhanced performance.

Textile Products for Civil Engineering Applications

Textile products are increasingly utilized in civil engineering due to their lightweight, high-strength, and cost-effective properties, offering sustainable alternatives to traditional materials. These textile applications contribute to innovative and environmentally friendly construction practices.

Key applications include:

- Geotextiles: Permeable materials used for soil stabilization, drainage, and erosion control in road construction and retaining walls.
- Geogrids: High-strength textiles that reinforce soils, enhancing bearing capacity for slope stabilization and soft soil reinforcement.
- Geomembranes: Impermeable membranes used for containment in landfill liners and water storage facilities.
- Reinforcement of Concrete: Materials like carbon, glass, and basalt fibers improve the strength and durability of concrete structures, reducing cracking.

- Tensile Structures: Lightweight structures made from PVC-coated polyester and PTFE-coated fiberglass, ideal for roofs and canopies.
- Architectural Membranes: Flexible textile membranes used in facades and roofs, allowing for creative designs.
- Reinforcement of Masonry**:** Carbon fiber is used to strengthen masonry structures, enhancing their durability and lifespan.

Reinforcement Bars (Rebar): Rebar is essential for reinforcing concrete structures, which are strong in compression but weak in tension. Made from carbon steel, rebar comes in various sizes and shapes, with deformed bars featuring ridged surfaces for better bonding with concrete. Common applications include buildings, bridges, tunnels, and highways, where rebar is placed in a grid pattern to enhance strength and stability. Proper installation is crucial to prevent structural failure, and rebar's tensile strength varies by diameter and grade, with common grades like ASTM A615 offering different yield and tensile strengths.

Important Characteristics of Rebar

1. Tensile Strength: High tensile strength is necessary to withstand forces and prevent cracking.
2. Ductility: Good ductility allows bars to deform under stress without breaking, preventing sudden failures.
3. Bond Strength: Strong adhesion between rebar and concrete is vital for effective load transfer.
4. Corrosion Resistance: Rebar must resist corrosion, especially in harsh environments, often requiring protective coatings.
5. Bendability: Bars should be bendable to fit design specifications.
6. Weldability: Good weldability is important for joining bars securely.
7. Cost-effectiveness: Rebar should be affordable and readily available for large construction projects.

Pros and Cons of Steel Rebar

Pros:

- High Strength: Excellent strength-to-weight ratio.

- Ductility: Can absorb energy and resist sudden failures.
- Bond Strength: Effective load transfer with concrete.
- Cost-effective: Widely available and affordable.
- Durability: Long service life when protected from corrosion.

Cons:

- Corrosion: Prone to rust, especially in coastal areas.
- Fire Susceptibility: Loses strength at high temperatures.
- Weight: Heavy, making handling and transport challenging.
- Environmental Concerns: Steel production has significant environmental impacts.
- Magnetism: Can interfere with sensitive equipment.

Fibre Reinforcement Rebars

Fibre reinforcement bars are composite alternatives to traditional steel rebar, made from materials like glass, carbon, or basalt embedded in a polymer or cement matrix.

Pros and Cons of Fibre Reinforcement Bars

Pros**:**

- Corrosion Resistance: Do not corrode, ideal for harsh environments.
- Lightweight: Easier to handle and transport than steel.
- High Strength-to-Weight Ratio: Stronger than steel on a per-weight basis.
- Easy Installation: Can be cut and shaped on-site.
- Electromagnetic Neutrality: Non-magnetic, suitable for sensitive applications.

Cons:

- Cost: Generally more expensive than steel, potentially limiting use.
- Brittle Behavior: Can fail suddenly without warning.
- Fire Resistance: May not be as fire-resistant as steel.
- Adhesion: Bonding with concrete may not be as strong as with steel.

Comparison Between Steel Rebar and FRP Bars

Fibre-reinforced polymer (FRP) rebar presents several advantages over traditional steel rebar, addressing some of steel's limitations:

1. **Corrosion Resistance**: FRP rebar is non-metallic and resistant to corrosion from moisture and chemicals, leading to longer service life and reduced maintenance.
2. **Lightweight**: Weighing about one-fourth of steel for equivalent strength, FRP rebar simplifies handling and installation, potentially lowering the dead load of structures.
3. **High Strength-to-Weight Ratio**: FRP rebar is stronger than steel for the same weight, allowing for the design of lighter, more slender structures without sacrificing safety.
4. **Non-Magnetic and Non-Conductive**: Suitable for sensitive environments, FRP rebar does not interfere with electronic devices and enhances electrical safety.
5. **Thermal Insulation**: With lower thermal conductivity than steel, FRP rebar helps reduce thermal bridging, improving energy efficiency in buildings.
6. **Design Flexibility**: Easily customizable, FRP rebar can be shaped on-site to meet specific design needs, facilitating installation around curves and corners.

Summary of Research on Composite Textile Fibre Reinforcement Bars

Research in composite textile fibre reinforcement bars focuses on enhancing their mechanical properties, durability, long-term performance, manufacturing techniques, bond behavior, cost-effectiveness, and sustainability. Key areas of study include:

- **Mechanical Properties**: Investigations into tensile, flexural, and shear behavior of composite bars compared to traditional steel reinforcement.
- **Durability**: Studies on resistance to corrosion, fatigue, and environmental degradation to ensure long-term performance.
- **Manufacturing Techniques**: Exploration of methods such as pultrusion, weaving, and braiding for producing composite bars.
- **Bond Behavior**: Assessing adhesion and bond strength between composite bars and concrete for effective structural applications.
- **Cost-Effectiveness and Sustainability**: Evaluating the economic feasibility and environmental benefits of using composite bars over conventional steel.

Prominent researchers include:

- **Prof. Antonio Nanni**: His work bridges theoretical research and practical application, focusing on concrete composition and environmental exposure to enhance the durability of fibre-reinforced polymer (FRP) bars. He advocates for sustainability through the use of recycled materials, demonstrating the economic and ecological benefits of such practices.
- **Prof. Anastasios Vassilopoulos**: Known for his expertise in filament winding techniques, he aims to produce high-quality, defect-free FRP bars efficiently, revolutionizing construction practices.
- **Dr. Sami Rizkalla**: His life-cycle cost analyses highlight the long-term savings associated with FRP bars, emphasizing the importance of considering the entire life cycle of construction materials.
- **Prof. Vistasp M. Karbhari and Prof. Lawrence C. Bank**: They focus on the environmental advantages of FRP bars, showing how integrating recycled materials can lower the carbon footprint of construction projects.
- **Dr. BrahimBenmokrane**: His research on the long-term performance of FRP bars under various environmental conditions ensures their reliability in concrete structures. He also explores low-cost fibers and resins to reduce production costs and carbon emissions.

- **Dr. J. G. Dai**: His work emphasizes the application of FRP bars in marine environments, addressing corrosion resistance and bond degradation over time, which is crucial for maintaining structural integrity in coastal infrastructure.
- **Dr. Mohamed Masmoudi**: Investigates degradation mechanisms of FRP composites due to moisture, temperature variations, and chemicals, enhancing understanding of their long-term performance.
- **Prof. L. C. Bank**: Evaluates creep behavior, thermal effects, and environmental aging of FRP composites, ensuring their structural integrity throughout their lifespan.
- **Dr. Mirmiran**: Studies creep behavior and fatigue resistance in FRP bars for bridge construction, confirming their resilience under varying loads over time.
- **Prof. Rao**: Highlights FRP bars' resistance to environmental conditions like freeze-thaw cycles and UV exposure, reinforcing their long-term durability.

- **Dr. Scott T. Smith**: Focuses on optimizing bond strength in FRP-reinforced structures, emphasizing the need for tailored applications to enhance performance and durability.
- **Prof. Vadim V. Silberschmidt**: Explores hybrid FRP bars for improved bond strength and durability, guiding the development of resilient composite solutions.
- **Dr. Yasuhiko Watanabe**: Develops hybrid FRP composites with enhanced durability against environmental degradation and mechanical wear.
- **Dr. Satish Kumar**: Refines the pultrusion process to improve the mechanical properties and manufacturing efficiency of FRP bars.
- **Dr. Habib Tabatabai**: Utilizes techniques like Resin Transfer Molding (RTM) to produce FRP bars with superior mechanical properties and reduced void content.
- **Prof. John Summerscales**: Enhances manufacturing processes through automated fiber placement, ensuring FRP bars meet demanding load requirements.
- **Dr. Thomas Keller**: Introduces thermoplastic composites for recyclability and processing efficiency, aligning with sustainable construction practices.
- **Prof. Ryszard J. Zalewski**: Innovates in braided and woven fiber architectures, improving the durability and production efficiency of FRP bars.
- **Dr. Ashfaq Adnan**: Explores additive manufacturing to enable complex geometries and customized solutions for FRP bars.
- **Prof. Luigi Ascione**: Pioneers hybrid manufacturing techniques for multifunctional composite bars, bridging traditional and innovative approaches.
- **Dr. P. Michael Schubel**: Focuses on rapid manufacturing to optimize cycle time and energy consumption, addressing modern infrastructure demands.
- **Prof. Peter Davies**: Advocates for eco-friendly methods using bio-based resins and natural fibers, ensuring high performance while minimizing environmental impact.

These researchers collectively advance the understanding and application of FRP composites, promoting sustainable and resilient construction practices.

Steel has been a staple in construction for reinforcement but has significant drawbacks, including susceptibility to corrosion, heavy weight, low strength-to-weight ratio, and limited design flexibility. In contrast, Fiber Reinforced Polymer (FRP) rebars, while resistant to corrosion, face challenges such as high costs, brittleness, and low rigidity. There is a pressing need for research on the long-term durability and bond behavior of FRP bars made from braided ropes and resin materials, especially under extreme conditions. Optimizing bond strength and

addressing related issues are crucial for effective structural applications. Braided composite rods may enhance tensile strength and bond performance, presenting a promising alternative to steel. Additionally, research focused on reducing the costs associated with FRP manufacturing and installation is essential for making these reinforcements more competitive. Addressing these gaps will help establish FRP bars as viable alternatives to traditional steel reinforcements in civil engineering and construction.

CHAPTER 3
MATERIALS AND EXPERIMENTAL METHODS

3.0 Introduction

This chapter provides a comprehensive overview of the materials and methodologies employed in this research. The efficacy and reliability of any research study largely depend on the appropriateness of the materials used and the robustness of the methodologies applied. This section serves as a comprehensive guide to the procedures and techniques employed to achieve the research objectives and validate the hypotheses. The selection of appropriate materials and the implementation of a rigorous methodological framework are pivotal in ensuring the reliability and validity of the study's findings. This chapter is divided into three sections, Section 1- Machine Modification, Section 2- Rope Preparation, and Section 3 - Rod Preparation, each detailing a specific aspect of the research design, including the selection of materials, data collection methods, experimental setup, and analytical techniques. Through this structured approach, we aim to provide a transparent and replicable account of the research process, facilitating a thorough understanding and critical evaluation of the study.

After assessing the performance of yarn, rope, and rod prepared from a given material of available size and dimension, predicting the beyond size is challenging. To predict the values of ropes & rods beyond the tested sizes, mathematical modeling becomes essential. For this study, the tensile behaviour of synthetic fiber ropes made from materials like polypropylene, nylon basalt, and their blends have been mathematically analysed. Here goal is to generate well-documented experimental statistics and develop simplified stress-strain constitutive laws that describe the ropes' tensile response. Here to predict this behaviour of rope and rod, various mathematical formulation based on python programs is used. Methods like Artificial Neural Networks (ANN), and Curve Optimization are used. All these methods and their outputs are discussed in a separate chapter.

To have a comprehensive understanding of the work, Chapter 3 has been further divided into different sections. Section I deals with machine modification, Section II deals with rope preparation of different diameters with the help of varied materials and Section III deals with the preparation of composite rods from the prepared ropes.

Section I

3.1 Machine Modification

The existing biaxial braiding machine was modified to facilitate the addition of third axial yarn which will be introduced at zero degrees, during braiding. Such a braiding machine is known as Tri-axial braiding. Apart from this, the take-up mechanism was also modified to achieve different take-up rates. Thus, modification was carried out in the existing machine and was made versatile for the manufacturing of biaxial as well as triaxial braided products[1]–[5].

Initial modification was made at the base of the machine i.e. at the creel section from where the core yarns are supplied. An additional creel was designed to accommodate an additional 8 supply packages. This creel was kept at the bottom of the machine, exactly below the horn gear (Figure 3.1). This will facilitate the addition of yarn exactly at zero degrees between the intertwining yarns. Additional spring and washer type of tensioning devices were also incorporated on the creel for individual yarn to maintain constant yarn tension and it will also prevent extra and loose yarn from being braided.

The second modification was conducted at the centre of the machine. i.e. between creel and take up section. A half-threaded solid bolt was provided to hold the horn gear and track plate assembly (Figure 3.2), which was replaced by a specially designed hollow bolt of the same dimension. The replacement of the hollow bolts at all positions (Figure 3.3, a &b) will not only hold the horn gear and track plate firmly but also will allow the central thread from the bottom creel to pass through it and clockwise and anticlockwise yarn will braid towards the central take-up unit[5]–[8].

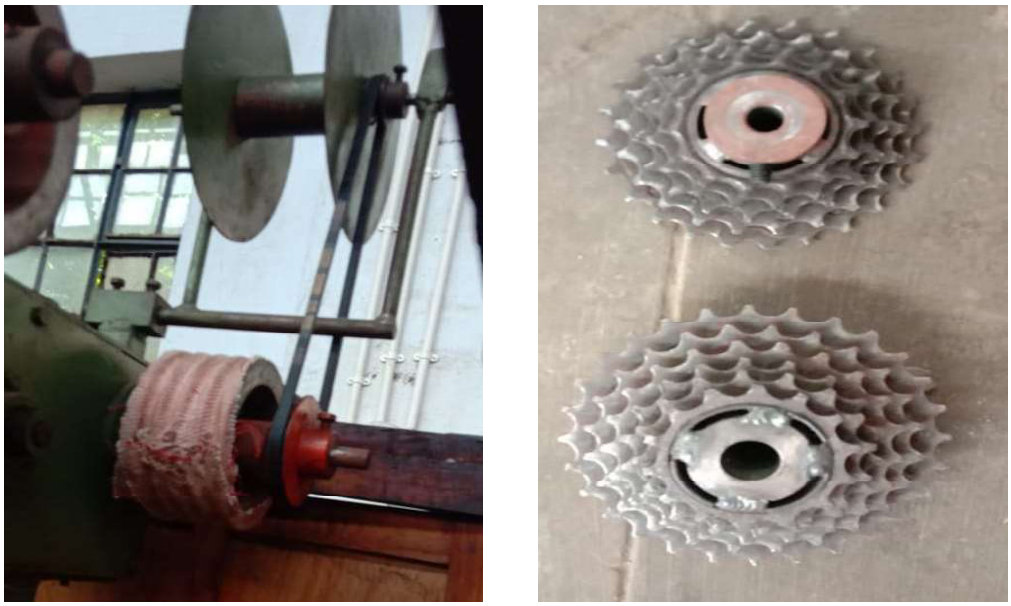
Figure 3.1 Tri-axial braiding machine

Figure 3.2 Nut &bolt at horn gear assembly for biaxial machine

(a)

(b)

Figure 3.3 Modification at horn gear assembly for triaxial machine



(a) *(b)*

Figure 3.4 Modification at take up zone for braiding machine

Further, in addition to the introduction of the third axial yarn, modification was also made to the take-up mechanism of the machine (Figure 3.4 & 3.5). The take-up mechanism controls the tension and speed of the braided material as it winds onto a spool. It is an important way to adjust the tightness factor of the braided structure, especially the angle of the braid. The modification of this mechanism enables the machine to achieve different take-up rates, providing greater flexibility in the manufacturing process.

Figure 3.5 Take up zone for braiding machine

Overall, the modifications made to the existing biaxial braiding machine make it versatile, and capable of producing both biaxial and triaxial braided products. This versatility is essential for meeting the specific requirements of different applications and expanding the range of products that can be manufactured using the modified machine. The adaptation of the machine to accommodate the third axial yarn and adjust the take-up mechanism demonstrates an innovative approach to enhance its functionality and broaden its applications in the field of braided materials manufacturing[9], [10].

Section II

3.2 Rope Preparation

We aim to make a braided composite rod to be used for civil engineering applications and the strength and diameter requirement of these rods should be comparable with the existing steel rods. So, high tenacity and high denier yarns of three different variants like Polypropylene, Nylon & Basalt were procured from Arrow Tech Textiles, Mumbai (Fig. 3.6). These basic yarns and their combination blends i.e. Basalt – Nylon and Basalt – Polypropylene were used for rope preparation.

Figure 3.6 Yarns procured for braiding

Researchers consider yarn strength to be a very important factor. Stronger yarns make better final products. Therefore, higher denier synthetic yarns, are used because they offer greater tensile strength & other mechanical characteristics compared to lower denier. For these trials, higher denier yarns with high tenacity material of three different variants, namely basalt, nylon,

and polypropylene are tried to get variety in the product range. To get more into to product category, blends like basalt – nylon and basalt – polypropylene also have been tried. The basic raw material characteristics are as follows shown in Table 3.1:

Table 3.1 Yarn characteristics

Yarn type	Yarn count	Maximum load [gf]	Maximum extension [mm]	Stress [gpd]	Strain (%)
3 ply PP	1500 Den	9269.64	24.29	6.17	24.29
4 ply Nylon	3550 Den	25532	20.15	7.19	20.15
Basalt	7200 Den	33082	2.86	4.59	2.87

3.2.1 Tri-axial Rope

The high-tenacity yarns procured were used as raw material for the manufacturing of triaxial braided ropes. Circular braided ropes are manufactured on a B&B braiding machine. This machine is running on the Maypole principle, which has 16 carriers. The diameter of the manufactured ropes was increased by the braid over braid technique. These desired diameter ropes are used as a reinforcement material and were further converted into rods using the method described in section 3.3.

1st lot of tri-axial braided rope production started with polypropylene yarn of given properties. Here in tri-axial braided rope regular braiding positions rotate in clockwise and anti-clockwise direction. i.e. 8 clockwise and 8 anti-clockwise, total 16 bobbins. Apart from this 8 bobbins were placed at zero degree position along with a single yarn core for the first layer. i.e. total of 25 yarns in the first layer. In this position about 100 meters of braided rope were prepared. From this about 20 meters of rope were cut and placed apart for 1st layer rope testing and rod preparation. The remaining 80 meter of rope is now ready for second layer build-up.

Now in the core, 1st layer braided rope was fed and second layer was braided above the first layer keeping all other parameters same. Similar kind of arrangements like 1st layer i.e. 8 bobbin will rotate in clock wise direction, 8 bobbin will rotate in anti-clockwise, total 16 bobbins. Along with it 8 bobbins were placed at zero degree position. I.e. Total 24 yarns and 1 core. This type of arrangement is known as braid over braid arrangement. In this condition we will

start the machine for another 80 meter braided rope. This is known as second layer braiding. From this about 20 meter of rope were cut and placed apart for 2nd layer rope testing and rod preparation. Remained about 60 meter of rope is now ready for Third layer build up.

In this similar manner, the third, fourth, and fifth layers are prepared each of 20 meters. The basic aim of adopting this braid over braid technology is to gain the higher diameter of braided rope and further with the rod. This higher diameter may contribute towards high tensile strength and other favourable mechanical properties.

The below given parameters describes the development of a variety of triaxial braid-over-braid ropes using different materials and techniques to achieve a range of strengths and other characteristics for a cost-effective product line.

Material Exploration:

- Experimented with various raw materials having different properties to create a diverse product range in terms of strength and other characteristics.
- Similar to the previously discussed polypropylene (PP) ropes, designed and produced triaxial braid-over-braid ropes using nylon and basalt fibers.

Diameter Variation:

- Using the same braiding technique, manufactured five different diameters for each type of rope (PP, nylon, and basalt).

Blended Rope Development:

- To further expand product offerings, created blended ropes using the triaxial braid-over-braid technique.
- This involved modifying the bobbin placement on the braiding machine.

Basalt-PP Blend:

- For the basalt-PP blend, position 100% basalt fibers in the axial direction (0 degrees) for maximum strength.
- The remaining braiding positions were filled with 100% polypropylene fibers at an angle.
- Similar to the pure PP ropes, produced five different diameters of this blended rope, each 20 meters long.

Nylon-Basalt Blend:

- Followed the same methodology to create a nylon-basalt blended rope with similar properties and production details.

In essence, created a variety of triaxial braid-over-braid ropes using different materials (PP, nylon, basalt) and blends (basalt-PP, nylon-basalt) with varying diameters to cater to a wider range of techno-commercial needs in terms of strength and other functionalities.

Section III

3.3 Rod Preparation

For the preparation of Braided composite rods, the prepared braided ropes are to be used as reinforcement and the matrix material needs to be applied. Selection of the right matrix material is very important, as it will finally decide the proper bonding with reinforcement for the desired application. Various types of resin and hardener combinations are available in the market. After a few initial trials with a couple of epoxy resins as well as a polyester base resin, we chose to go with the epoxy resin CTE556 and the hardener material CTAH951. The basic details of the resin and hardner used are as given in Table 3.2, 3.3, 3.4. [Procured from Composite tomorrow, Vadodara].

Table 3.2 Characteristics of resin& Hardner

Characteristic	Test Method	Unit	CT/E-556 [Resin]	CT/AH-951 [Hardener]
Viscosity at 25°C	ASTM-D 2196	mPa·s	9,000 - 12,000	110 - 120
Flash Point	ASTM-D 93	°C	> 200	> 200
Density at 25°C	ASTM-D 4052	g/cc	1.15 - 1.20	0.97 - 0.99
Epoxy Content	ASTM-D 1652	Eq/Kg	5.3 - 5.45	-

Table 3.3 Mechanical and Physical Properties of resin& Hardner

Property	Test Method	Unit	Value
Tensile strength	ASTM:D638	N/mm²	70-80
Elongation at break	ASTM:D638	%	2.0-2.2
Flexural strength	ASTM:D790	N/mm²	90 - 100
Glass transition temperature (DSC)	ASTM: D3418	°°C	70-80

Table 3.4 Electrical Properties of resin& Hardner

Property	Test Method	Unit	Value
Dielectric strength	IEC 60243-1	KV/mm	23-25
Dielectric dissipation factor	IEC 60250	%	1.2 -1.3
Dielectric Constant	IEC 60250	-	4-4.2
Volume Resistivity	IEC 60093	Ohm cm	> 10^15

CTE556 is a modified epoxy laminating resin designed for high-performance applications. CTAH951 is a modified polyamine-based hardener suitable for high mechanical performance applications in static and dynamic load conditions.

The hardener CTAH951 of this system can provide a pot life of >5 hours at 25ºC with low exothermic reactions, even when it is used for higher thickness components of large size. The low initial viscosity of this system ensures fast and complete impregnation of reinforcement in fibers such as glass, carbon, polyamide, and polyester. It allows components to be produced by various process techniques with high consistency in performance properties. The components cured at room temperature provide excellent handling strength (Fig. 3.9).

3.3.1 Hand Lay Process

The application of a matrix on the surface of a rope is essential, especially when dealing with braid over braid ropes. The binding of individual layers can be challenging, and this is where the resin comes into play. To ensure uniform resin penetration inside the rope matrix, a small calendaring machine was developed. This machine, as depicted in Figure 3.10, consists of two heavy rolls housed in a bearing and mounted in a steel frame. One of the rollers is equipped with a handle to facilitate rotation. The resin-impregnated rope is passed through these rollers, allowing for proper penetration of the resin into the layers and removal of excess matrix material. This process is repeated two to three times to ensure proper impregnation of resin into the reinforcement material.

It was noted that the shape of the prepared Braided Composite Rod (BCR) became deformed due to squeezing, and a proper circular cross-section was not achieved. To rectify this, the braided ropes were passed through desired circular shape pre-forms. This process allowed the deformed braided rope to regain its original shape and size.

The resin solution used in the braided ropes was a mixture of CTE556 (Epoxy resin) and hardener CTAH951, maintained at a ratio of 10:1. The curing of this resin within the braided

rope is a crucial factor, as it needs to result in a straight rod-like structure. The curing process takes place at room temperature. Arrangements were made to hang the resin-applied ropes vertically, allowing the ropes' self-weight to straighten them. The ropes were left in this position for about 24 hours to cure, hardening the rope and converting it into a rod-like structure.

Figure 3.11 illustrates the preparation of the resin mixture. The rope is converted into a composite form using a hand-laying method. This involves manually mixing the resin and hardener and applying them to the braided ropes. The material is then left on the desired base for the next 24 hours at room temperature.

Due to the viscosity of the resin, it would have been challenging for it to penetrate the core of the rope. To improve its penetration, the braided rope was unwound from the bobbin, passed through the resin bath, squeezed manually, and then dipped again into the resin bath. This process allowed the air from the sample to escape and facilitated resin impregnation to the core. The rope was squeezed again before drying to ensure proper impregnation of the resin into the reinforcement material (Figure 3.12). The repetitive squeezing disturbed the circular shape of the braided rope. To restore its shape, the resin-impregnated rope was immediately passed through a circular-shaped funnel, giving the rod a proper diameter. Different layers of ropes required different funnel diameters. All the samples were then hung on a wire for the next 24 hours at room temperature (figure 3.13). After 4 to 5 hours, the samples began to solidify, and complete solidification required 24 hours.

A total of 25 samples, each with 5 layers and 5 raw material combinations, were prepared using this hand-lay method. All braid rope samples have now been converted into composite rod form, referred to as a Braided Composite Rod (BCR). The braid angle and diameter of the BCR are mentioned in the table below. All 5 materials were braided with a uniform take-up speed to maintain almost uniform braiding parameters, as shown in Table 3.5. The entire sample set is now ready for testing. All the samples were precisely cut into the required shape and size to carry out tests as per the standards.

Figure 3.12 Manual hand lay preparation

Figure 3.13 Curing treatment for braided rod preparation

Table 3.5 Parameters of braided composite rods

Composite sample Code	Layer (mm)	Braid angle (Degree)
BCR	1	28
BCR	2	34
BCR	3	41
BCR	4	48
BCR	5	54

CHAPTER 4
RESULT AND DISCUSSION

4.0 Introduction

This chapter describes the analysis of various properties of the prepared samples which have been obtained using the appropriate equipment in the standard testing condition. Results obtained from the various tests mentioned in Chapter 3 are compiled and discussed herewith, for their application in various areas. In line with Chapter 3, this chapter is also divided into two sections. Section 1 deals with the analysis and comparison of results obtained from yarn and prepared triaxial braided rope with individual raw material and their different combinations. Section 2 deals with the analysis and comparison of results obtained from prepared braided composite rods with individual raw material and their different combinations.

For better understanding, Table 4.1 exhibits the experimental design which gives information regarding the materials used, their combinations, the number of samples prepared and different tests conducted. In totality, 235 tests were performed on 25 different combinations of ropes and rods each.

Table 4.1 Experimental design

Independent variables	Dependent Variables		Analysis	Characteristics
Raw material	PP	BCRs were prepared using individual raw material for 5 different layers making total 25 combinations. Analysis was conducted starting for yarn, rope and rod and further analysed for different combinations.	Yarn	Linear Density
	Nylon			Mechanical Properties
	Basalt		Rope	Linear Density
	PP: Basalt			Mechanical Properties
	Nylon: Basalt			Braid parameters
Layers	First			Blend analysis
	Second		Rod	Linear Density
	Third			Fibre Volume Fraction
	Fourth			Mechanical Properties
	Fifth			Bond characteristics
				Flexural strength

4.1 Characterization

4.1.1 FTIR Spectroscopy for Resin

Figure 4.1 displays FTIR spectra of epoxy resin. The X-Axis indicates wavenumbers (cm-1) ranging between 4000 cm-1 to 400 cm-1 and the Y-Axis indicates transmittance (%T). The presence of bands at 862.74 cm-1 and 915.15 cm-1 (both C-O deformation) corresponds to epoxide ring vibrations, 1246.97 cm-1 correspond to asymmetrical C-O. Stretching vibration of C-C in aromatic rings appeared at 1510.41 cm-1. Narrow peak between 2900 cm-1 to 3000 cm-1 represent asymmetrical C-H stretch of -CH3 group. The presence of broad band at 3493.45 cm-1 indicates the presence of -OH stretching. The presence of important functional groups of epoxy resin was verified according to its chemical structure.

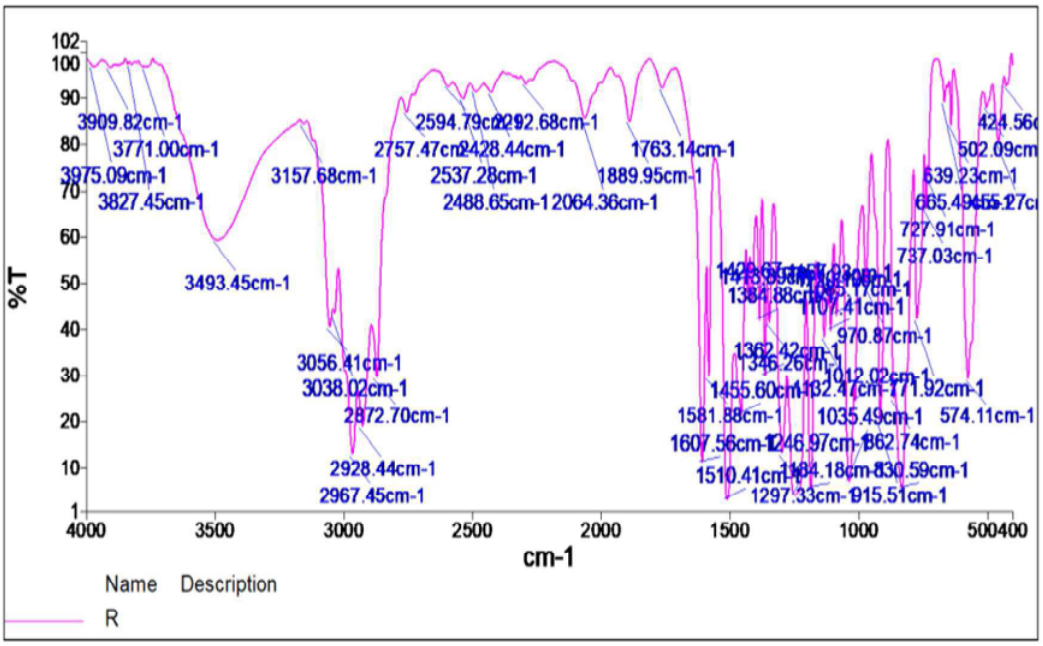


Figure 4.1 FTIR image for resin

4.1.2 FTIR Spectroscopy for Hardener

Figure 4.2 displays FTIR spectra of hardener for epoxy resin. The X-Axis indicates wavenumbers (cm-1) ranging between 4000 cm-1 to 400 cm-1 and the Y-Axis indicates transmittance (%T). The peak at 3368 cm-1corresponds to the stretching vibration of -NH group. Sharp Peaks at 2948 cm-1, and 2850 cm-1, represent the stretching vibrations of -CH bonds. Small Peak at 1869 cm-1 could be related to a carbonyl group (C=O). C=C Stretch (Small Peak near 1644 cm-1) indicates the presence of carbon-carbon double bonds (alkenes).

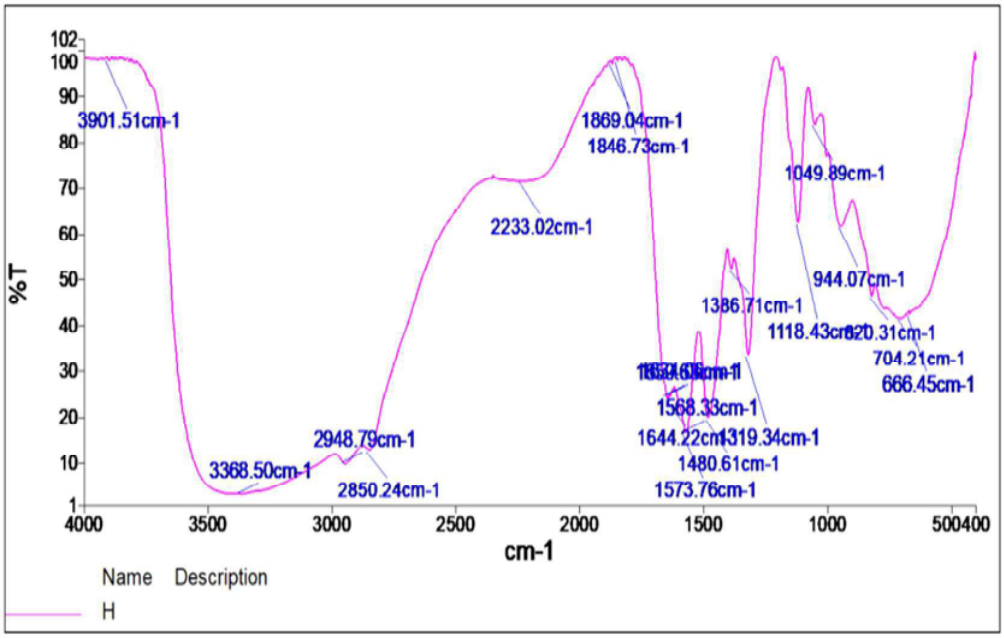


Figure 4.2 FTIR image for hardener

SECTION I

4.2 Yarn Properties

The yarn characteristics are important for choosing the right yarn for a particular application. Figure 4.3 provides information about different types of yarns procured and their test results. Basalt yarn has the maximum load-bearing capacity but a low extension & stress value, this may be due to the brittle nature of basalt fiber. Polypropylene has moderate values for both load and extension whereas nylon has high load-bearing capacity with maximum stress value but lower extension compared to PP. The selection of yarn was conducted based on high tenacity values suitable for required applications.

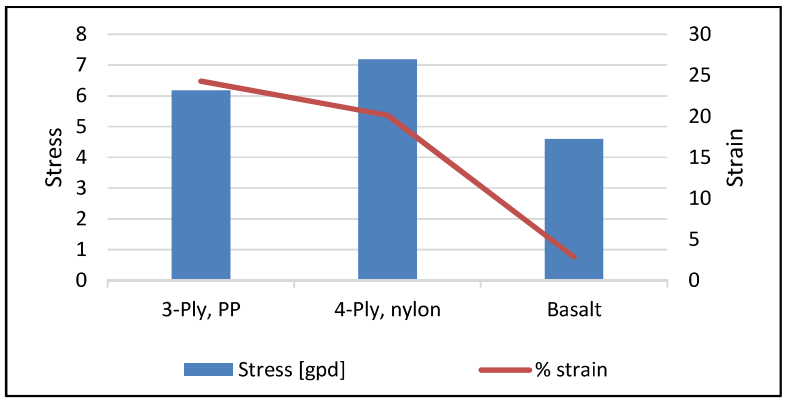


Figure 4.3 Yarn stress-strain analysis

4.3 Analysis of Braided Rope

Tri-axially braided ropes made from Basalt, PP, and Nylon & and their combinations [Figure No 4.4] are discussed here for their linear density and tensile characteristics. Further, their comparison is made with relevant fiber, yarn, and its strength characteristics.

4.3.1 Linear Density

Linear density is a measure of mass per unit length which is an important parameter in braided composite rods. Table 4.3 represents the linear density of various ropes across multiple layers, where 100% basalt ropes represent higher linear density due to higher density of basalt fiber i.e., 2.53 g/cc.

Table 4.3 Braided rope linear density

Layer	Material linear density in grams/ linear meter				
	PP	Nylon	Basalt	PP + Basalt [35:65]	Nylon+ Basalt [50:50]
1	4.38	10.49	19.73	11.3	12.85
2	8.62	20.82	39.74	19.9	23.5
3	13.06	31.47	58.57	28.5	35
4	17.19	42.49	81.27	39	45.65
5	21.51	52.98	93.97	51.5	58.25

Basalt ropes are being followed by basalt- nylon blended ropes as it consists of 50% of basalt yarn and 50% of nylon yarn. Nylon ropes stand in third position as nylon fibres possess a density of 1.14 g/cc which is higher than PP but lower than basalt. This is being followed by a PP-basalt blend and 100% pp braided ropes as PP has the lowest fibre density of 0.91 g/cc. Table 4.3 Material linear density in Grams/ Linear Meter for different layers All materials exhibit a similar increase in linear density across layers, except for a minor difference in the increased pattern of basalt composition. It suggests an accumulation of mass per unit length with the addition of each layer.

Polypropylene

Nylon

Basalt

PP : Basalt

Nylon : Basalt

Figure 4.4 Prepared Braided ropes with different material

4.3.2 Comparison of Tensile Properties: Between Layers

4.3.2.1 Polypropylene braided rope

The tensile test results for Polypropylene (PP) braided ropes, indicate a clear trend of increasing maximum force and rope g/lm with each successive layer, while the maximum displacement remains relatively consistent. Starting with the first layer, the rope could withstand a force of 513.30 Kgf with the extension of 64.55 mm, and to the fifth layer which exhibits a significant jump in the maximum force of 1051.51 Kgf with a displacement of 68.25 mm. Figure 4.6

combines bar and line graph which exhibit percentage increments in tensile strength of prepared PP ropes with different layers.

Figure 4.5 Tensile Testing for rope prepared from different material

It can be observed that with an increase in the number of layers, the strength percentage increases as well as the g/lm value also increases. The graph suggests a linear increment in terms of tensile strength and g/lm with the increase in layers. Considering the first layer as 100%, it is observed that the subsequent layers increase by 122.33, 133.01, 144.66, and 204.85 respectively from the second to fifth layer.

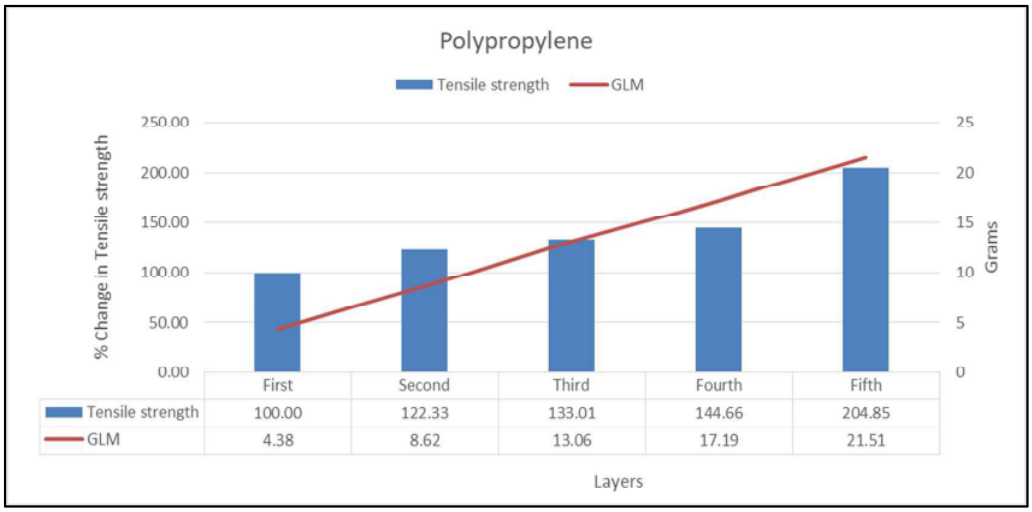


Figure 4.6 Percentage change in tensile strength

This data suggests that as the number of layers in PP braided ropes increases, the rope's ability to handle greater force, which is reflected in the rising rope g/lm values. The consistent displacement values suggest that the material maintains a stable elongation under stress across

all layers. These characteristics are crucial for applications where ropes are expected to sustain heavy loads without significant stretching.

4.3.2.2 Nylon braided rope

The tensile test results for nylon braided ropes, reveal a consistent increase in maximum force and rope g/lm with each additional layer, while the maximum displacement exhibits a slight fluctuation. The first layer of nylon rope withstands a maximum force of 657.82 Kgf, stretching to 53.79 mm, and has a rope g/lm of 10.49 to the fifth layer which demonstrates a substantial increase in maximum force of 1392.05 Kgf with the displacement of 50.30 mm. Figure 4.7 combines bar and line graphs which exhibit percentage increments in tensile strength of prepared nylon ropes with different layers. It can be observed that with an increase in the number of layers, the strength percentage increases, as well as the g/lm value, also increases. The graph suggests a linear increment in terms of tensile strength and g/lm with the increase in layers. Considering the first layer as 100%, it is observed that the subsequent layers increase by 143.94, 163.13, 175.25, and 211.62 respectively from the second to fifth layer.

These results indicate that nylon braided ropes significantly enhance their load-bearing capacity with each layer, as evidenced by the increasing rope g/lm values. There is a negligible difference in the maximum displacement values, which will not affect the performance of the material.

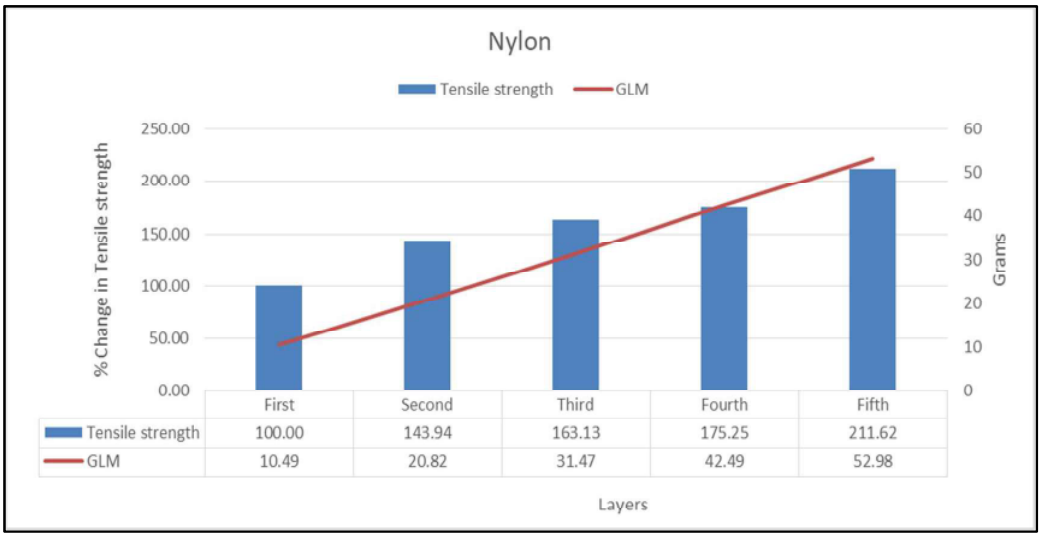


Figure 4.7 Percentage change in tensile strength

This data suggests that as the number of layers in Nylon braided ropes increases, the rope's ability to handle greater force, which is reflected in the rising rope g/lm values. The consistent

displacement values suggest that the material maintains a stable elongation under stress across all layers. These characteristics are crucial for applications where ropes are expected to sustain heavy loads without significant stretching.

4.3.2.3 Basalt braided rope

The tensile test results for basalt braided ropes, demonstrate a progressive increase in maximum force and rope g/lm across the layers, with a notable consistency in maximum displacement. The first layer of basalt rope withstands a maximum force of 508.32 Kgf whereas the second, third, fourth, and fifth layer exhibits maximum force of 601.34, 900.35, 973.44, and 1073.11 kgf respectively.

Figure 4.8 combines bar and line graphs which exhibit percentage increments in tensile strength of prepared Basalt ropes with different layers. It can be observed that with an increase in the number of layers, the strength percentage increases, as well as the g/lm value, also increases. The graph suggests a linear increment in terms of tensile strength and g/lm with the increase in layers. The consistent growth in rope g/lm values highlights the ropes' enhanced performance with each additional layer, affirming their suitability for heavy-duty usage where strength and stability are paramount. This data suggests basalt braided ropes exhibit outstanding tensile properties, making them a reliable choice for strenuous tasks.

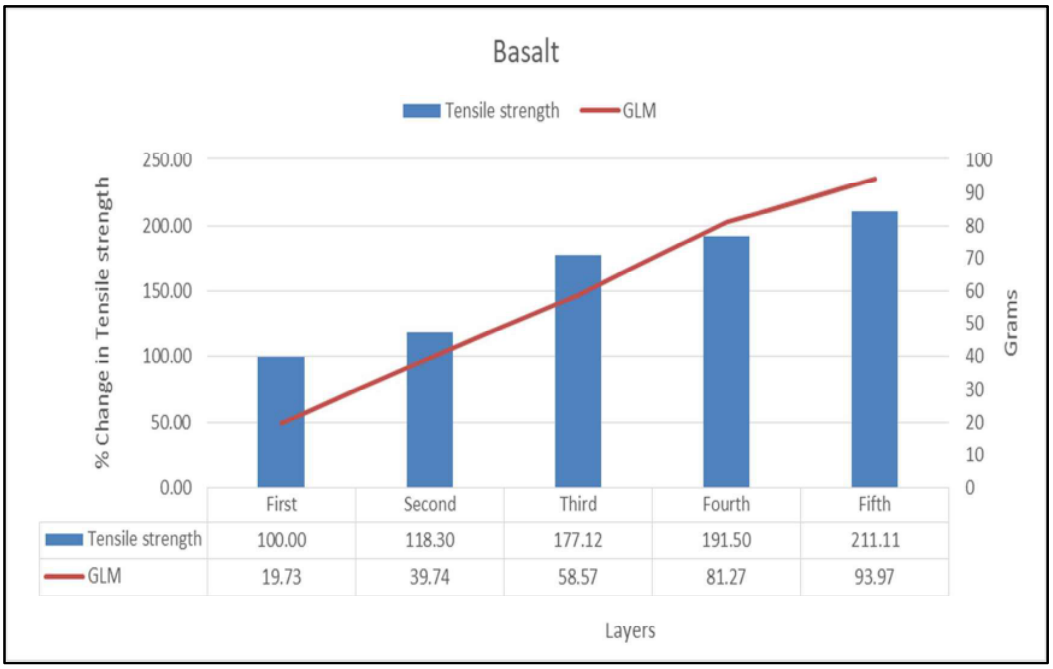


Figure 4.8 Percentage change in tensile strength

4.3.2.4 PP + basalt braided rope

The tensile test results for PP + basalt blended braided ropes, demonstrate a progressive increase in maximum force and rope g/lm across the layers, with a notable consistency in maximum displacement. The first layer of PP + basalt rope withstands a maximum force of 621.27 Kgf whereas the second, third, fourth, and fifth layer exhibits maximum force of 631.24, 694.36, 863.80, and 847.19 kgf respectively. These blended ropes exhibit significant increments in the maximum displacement values which is much higher than 100% basalt ropes, which can be due to the higher maximum displacement values of 100% PP ropes.

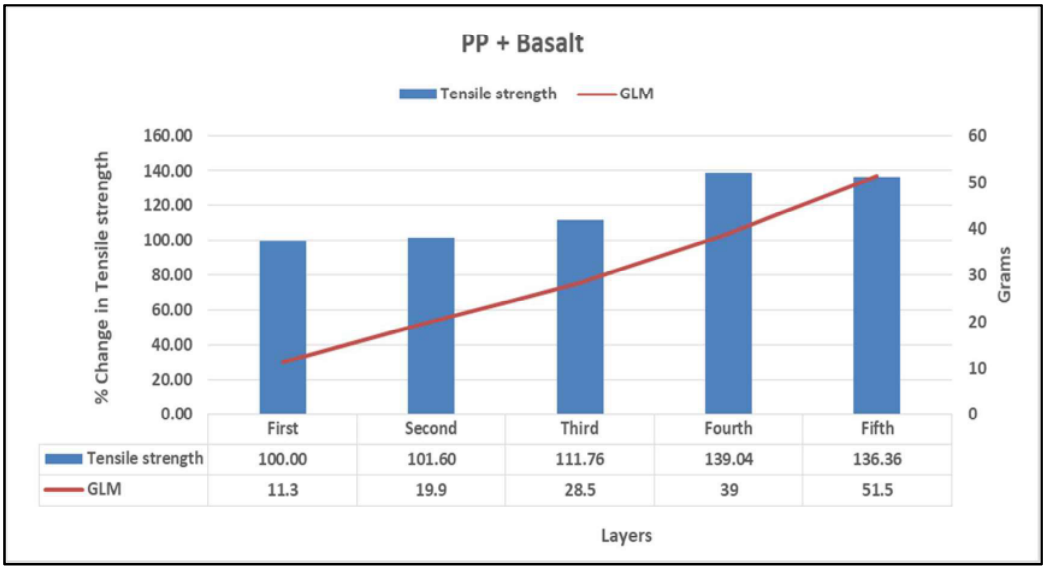


Figure 4.9 Percentage change in tensile strength

Figure 4.9 combines bar and line graphs which exhibit percentage increment in tensile strength of prepared PP + Basalt ropes with different layers. It can be observed that with the increase in the number of layers, the strength percentage increases, as well as the g/lm value, also increases. The graph suggests a linear increment in terms of tensile strength and g/lm with the increase in layers. It can be further analysed from the graph that the percentage increase in the load-bearing capacity of the prepared blend sample is not much as compared to individual PP and basalt ropes. This may be due to less inter-fiber friction between pp and basalt yarn which leads to lesser values of maximum force.

Overall, the data suggests variations in both force and displacement across layers, highlighting the material's performance under different conditions and aiding in informed decision-making for different structural applications in terms of mechanical properties and cost.

4.3.2.5 Nylon + basalt braided rope

The tensile test results for Nylon + basalt blended braided ropes, demonstrate a progressive increase in maximum force and rope g/lm across the layers, with a notable consistency in maximum displacement. The first layer of Nylon + basalt rope withstands a maximum force of 523.27 Kgf whereas the second, third, fourth and fifth layer exhibits maximum force of 593.03, 694.36, 867.13 and 1003.34 kgf respectively. These blended ropes exhibit significant increments in the maximum displacement values which is much higher than 100% basalt ropes, which can be attributed to higher maximum displacement values of 100% Nylon ropes.

Figure 4.10 combines bar and line graphs which exhibit percentage increment in tensile strength of prepared Nylon + Basalt braided ropes with different layers. It can be observed that with the increase in the number of layers, the strength percentage increases, as well as the g/lm value, also increases. The graph suggests a linear increment in terms of tensile strength and g/lm with the increase in layers. It can be further analyzed from the graph that the percentage increase in the load-bearing capacity of the prepared blend sample is not much as compared to individual nylon and basalt ropes. This may be due to less inter-fibre friction between nylon and basalt yarn which leads to lesser values of maximum force.

Overall, the material demonstrates progressively higher force capabilities across layers, while maintaining a moderate level of displacement. This information aids in understanding the material's performance characteristics in various structural applications, facilitating informed decision-making for different structural applications in terms of mechanical properties and cost.

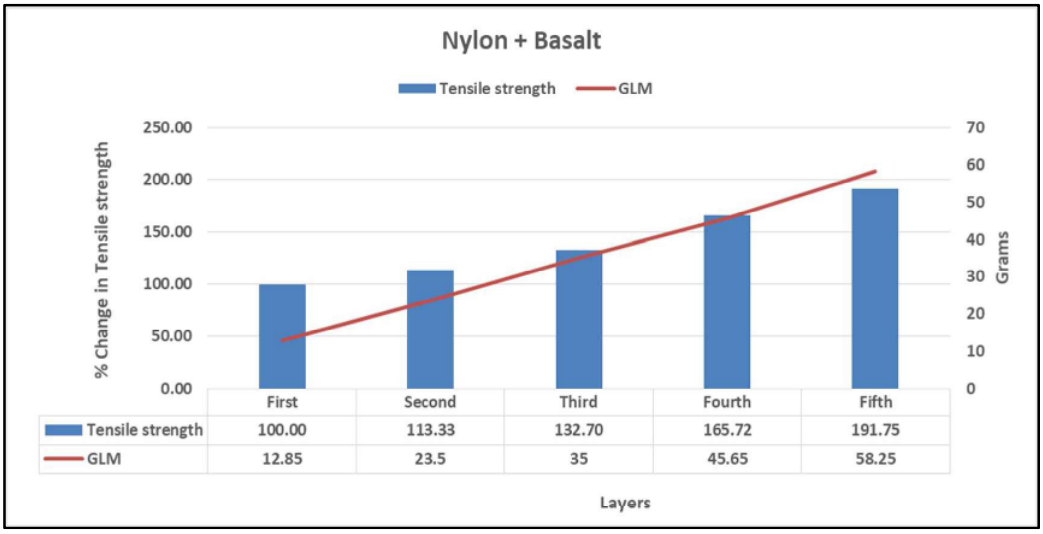


Figure 4.10 Percentage change in tensile strength

4.3.3 Comparison of Tensile properties: within Layer

4.3.3.1 First layer

The tensile test results for the first layer of braided ropes, Figure 4.11, reveal insights into the performance of different materials.

It can be observed that the Polypropylene (PP) rope exhibited a maximum force of 513.30 Kgf and a maximum displacement of 64.55 mm, at a Rope g/lm of 4.38. In contrast, the Nylon rope demonstrated superior strength with a maximum force of 657.82 Kgf, with a lesser displacement of 53.79 mm, at rope g/lm of 10.49. The Basalt rope, while having a comparable maximum force (508.32 Kgf) to the PP rope, had a significantly lower maximum displacement (5.38 mm), with the highest rope g/lm of 19.73 among the single-material ropes. When it comes to blended ropes, the PP + Basalt [35:65] rope showed a higher maximum force (621.27 Kgf) than the single-material ropes and a moderate displacement (18.83 mm), at a Rope g/lm of 11.30. The Nylon + Basalt [50:50] rope, on the other hand, had a maximum force (523.27 Kgf) similar to the PP and Basalt ropes but a lower displacement (16.14 mm), at a Rope g/lm of 12.85.

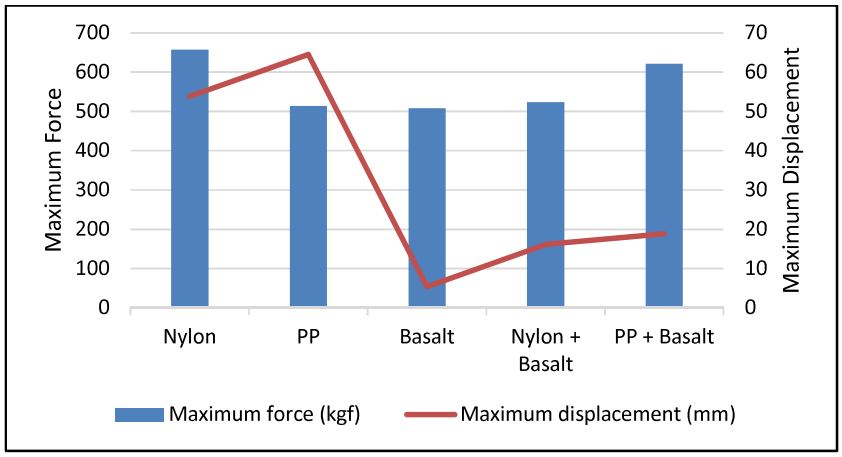


Figure 4.11 Stresss-strain behaviour of first layer

Low maximum force in basalt rope can be possibly due to the brittleness of the fibres which may have broken during rope preparation as well as material handling. Figure 4.11 helps in understanding which material or combination of materials might be best suited for applications requiring specific mechanical properties. For instance, if high force resistance is needed with low displacement, PP + Basalt [35:65] might be a good choice. If only high force resistance is

needed regardless of displacement, nylon could be considered.

4.3.3.2 Second layer

The tensile test results for the second layer of braided ropes, as shown in Figure 4.12, provide a comparative analysis of the performance of different materials. The Polypropylene (PP) rope in the second layer demonstrated a maximum force of 627.92 Kgf and a maximum displacement of 66.52 mm, with a Rope g/lm of 8.62. The Nylon rope showed a significant increase in strength with a maximum force of 946.86 Kgf and a displacement of 55.43 mm, at a high Rope g/lm of 20.82. The Basalt rope, while having a maximum force (601.34 Kgf) similar to the PP rope, had a much lower maximum displacement (5.54 mm), with impressive Rope g/lm of 39.74.

For the composite ropes, the PP + Basalt [35:65] rope showed a slight increase in maximum force (631.24 Kgf) compared to the single-material ropes and a moderate displacement (19.40 mm), with a Rope g/lm of 19.90. The Nylon + Basalt [50:50] rope had a maximum force (593.03 Kgf) similar to the PP and Basalt ropes but a lower displacement, (16.63 mm), at a Rope g/lm of 23.50. This data can be useful for selecting materials based on the required mechanical properties for specific applications in the second layer of a structure.

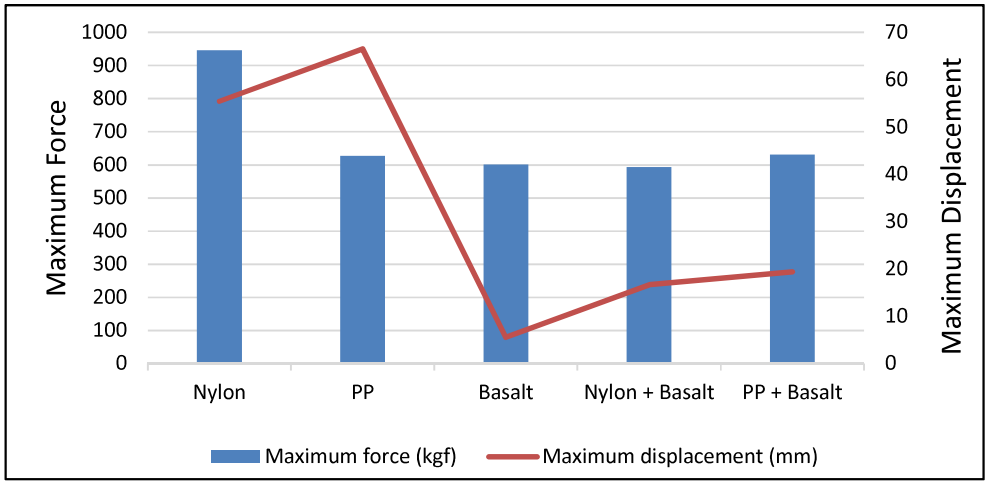


Figure 4.12 Stress-strain behaviour of second layer

4.3.3.3 Third layer

The tensile test results for the third layer of braided ropes, reveal significant variations in performance among different materials. Figure 4.13 compares the maximum force and maximum displacement for different materials, helping in the selection of materials based on the required mechanical properties for specific applications in the third layer of a structure. Nylon in the third layer has the highest maximum force, making it suitable for

applications requiring high strength, but it also has a high displacement. PP has the highest displacement, which might be a concern for applications requiring minimal deformation. Basalt has a high force and the lowest displacement, indicating it is strong and very stable. It should also be noted that as the number of layers increases in the basalt ropes the maximum load bearing capacity also increases compared to pp showing the impact of basalt fibre. Nylon + Basalt [50:50] and PP + Basalt [35:65] combinations offer a balance, with both having the same maximum force but different displacements, making them suitable for applications requiring moderate strength and low to moderate displacement.

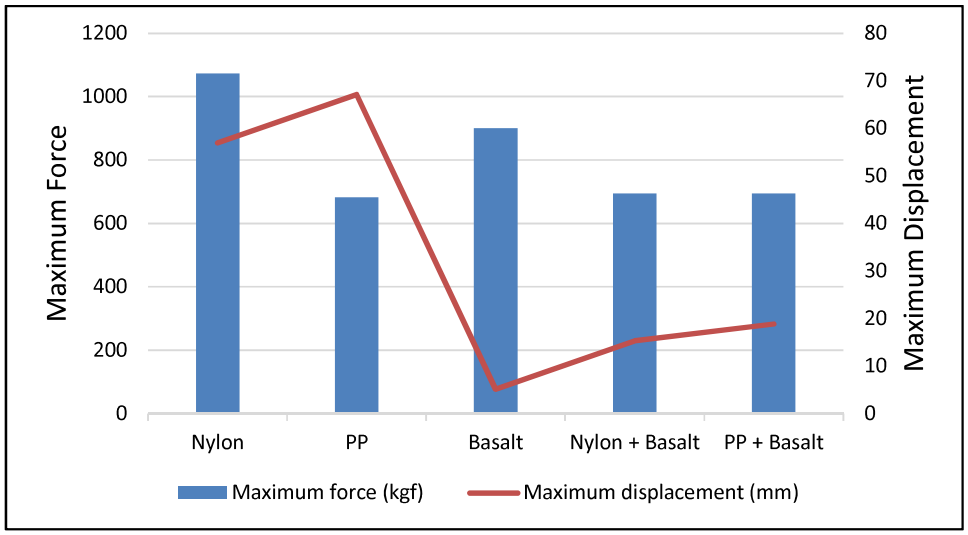


Figure 4.13 Stresss-strain behaviour of third layer

4.3.3.4 Fourth layer

The tensile test results for the fourth layer of braided ropes is presented in Figure 4.14. It shows polypropylene (PP) ropes registered a maximum force of 742.54, nylon exhibited 1152.5 kgf, basalt 973.44 kgf. This suggests that Basalt ropes possess superior tensile strength and minimal elongation under load, making them highly efficient in terms of energy absorption and resistance to stretching. The blend of PP + Basalt [35:65] and Nylon + Basalt [50:50] shows maximum force of 863.80 Kgf and 867.13 Kgf respectively. These results suggest that the integration of Basalt fibres into PP and Nylon ropes enhances their overall tensile properties, offering a compromise between strength and elasticity.

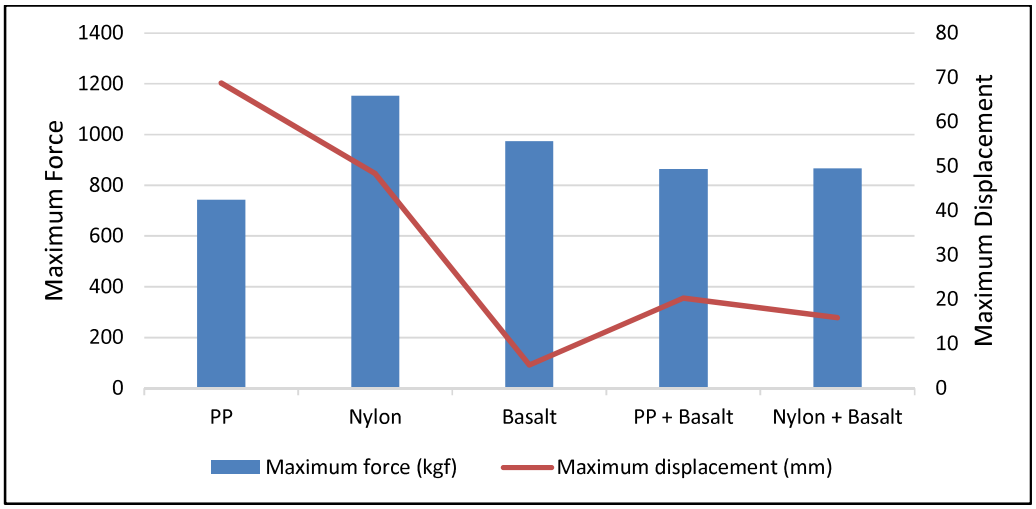


Figure 4.14 Stresss-strain behaviour of fourth layer

4.3.3.5 Fifth layer

The tensile test results for the fifth layer of braided ropes, presented in Figure 4.15, reveal a distinct performance profile for each material tested. The Polypropylene (PP) ropes showed a maximum force of 1051.51 Kgf and a displacement of 68.25 mm. The Nylon ropes, on the other hand, exhibited a higher maximum force of 1392.05 Kgf and a lower displacement of 50.30 mm.

The Basalt ropes stood out with a maximum force of 1073.11 Kgf and a minimal displacement of 4.67 mm. This indicates that Basalt ropes have exceptional tensile strength and very little elongation when subjected to force, which is advantageous for applications where high load-bearing capacity and minimal stretch are desired. The PP and Basalt blend recorded a maximum force of 847.19 Kgf, a displacement of 21.80 mm. Whereas, the Nylon and Basalt blend showed a maximum force of 1003.34 Kgf, a displacement of 15.41 mm.

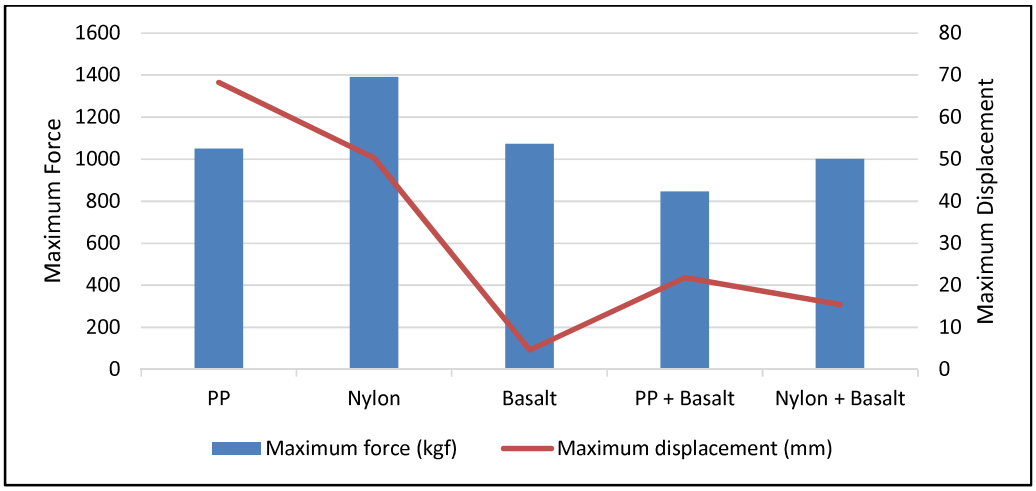


Figure 4.15 Stress-strain behaviour of fifth layer

Section II

Analyzing the physical specifications of braided rods for varying diameters and materials is essential for engineers across industries. This analysis helps in understanding mechanical properties like tensile strength and elasticity, ensuring durability and reliability while optimizing performance for specific applications. It helps for cost-effective decisions by balancing performance requirements with budget constraints and enables customization for specific applications. Moreover, it ensures safety and compliance with industry standards, crucial in sectors like civil engineering. Finally, this analysis empowers engineers to design, manufacture, and use braided rods effectively, considering factors such as mechanical properties, cost, safety, and performance optimization.

4.4 Fiber Volume Fraction Analysis

Fiber Volume Fraction is a measure of how much fiber is in a composite material. It is a ratio that tells you the amount of fiber compared to the total volume of the composite. The amount of fiber in the composite affects its mechanical properties like strength and stiffness. More fiber can make the composite stronger and stiffer. So, by changing the fiber volume fraction, we can adjust these properties. The fiber volume fraction also helps maintain a good balance between the fiber and the resin or polymer.

Polypropylene BCR

Nylon BCR

Basalt BCR

PP Basalt BCR

Nylon Basalt BCR

Figure 4.16 Braided Composite rods prepared from various materials

This balance is important for the composite to perform well. Because fibers are long and cylindrical, they can make the composite stronger in the direction they're laid. By changing the fiber volume fraction and the way the composite is made, we can customize its properties to suit different needs. This makes composite materials very versatile and suitable for a wide range of applications. The fiber volume fraction plays a pivotal role in determining the performance and application of textile composites. It allows for the customization of the composite material's properties, making it suitable for a wide range of applications.

4.4.1 Polypropylene BCR

Table 4.14 illustrates the fiber volume fraction across different layers of polypropylene (PP) material. The table details the composition of each layer, including measurements of rope in grams per linear meter, resin content, rod content, and the volume fraction of fibers. In the initial layer, the fiber volume fraction is 0.41, indicating that fibers constitute approximately

41%. The composition of this layer is balanced, with a notable presence of resin in rod. As we progress to the second layer, there's an increase in rope content, leading to a higher fiber volume fraction of 0.52. This increase suggests an enhancement in fiber reinforcement, which likely contributes to improved mechanical properties. Layer 3 stands out with the highest fiber volume fraction of 0.54, indicating optimal fiber integration. The equilibrium among rope, resin, and rod elements in this layer contributes to the material's rigidity and strength.

However, beyond layer 3, there is a slight decrease in the fiber volume fraction. Despite having higher rope content, layers 4 and 5 exhibit lower fiber fractions, suggesting a point of diminishing returns in terms of reinforcement. It fluctuates across layers, suggesting that other factors such as fiber arrangement or distribution influence the efficiency of fiber utilization. It appears that beyond a certain threshold, the penetration of more resin is becoming more difficult. Data Table 4.14 suggests here the key to optimizing the performance of a material like PP lies in achieving the perfect balance of fiber content. While layer 3 showcases the highest volume fraction of fibers, layers 4 and 5 demonstrate diminishing returns. This information is invaluable for engineers and designers as they can leverage it to customize material compositions for specific applications, keeping in mind both strength and cost-effectiveness.

Table 4.14 Fiber volume fraction in polypropylene BCR

Material	Layer	Rope g/lm	Resin g/lm	Rod g/lm	Fiber Volume Fraction
PP	1	4.38	8.50	12.88	0.41
PP	2	8.62	10.80	19.42	0.52
PP	3	13.06	15.21	28.27	0.54
PP	4	17.19	24.05	41.24	0.50
PP	5	21.51	36.49	58.00	0.45

4.4.2 Nylon BCR

Table 4.15 provides insights into the fiber volume fraction across different layers of nylon material. The first layer shows a high fiber volume fraction of 0.85, suggesting that fibers make up approximately 85% of the material. This may be due to application of high-pressure during manufacturing process being a hand lay-up method. Transitioning to the second layer, there is an increase in rope content, but the fiber volume fraction drops to 0.59. This layer achieves a balance between reinforcement and resin content. Layer 3 sustains a moderate fiber volume

fraction of 0.54. With a higher resin content of 29.72 g/lm, this layer suggests a more balanced composite.

In the fourth and fifth layers, the rope content continues its upward trend, leading to a marginal increase in the fiber volume fraction. These layers follow a similar pattern to layer 2, emphasizing reinforcement. This information allows engineers to customize material compositions based on specific needs, taking into account factors like strength, stiffness, and cost-effectiveness.

Table 4.15 Fiber volume fraction in nylon BCR

Material	Layer	Rope g/lm	Resin g/lm	Rod g/lm	Fiber Volume Fraction
Nylon	1	10.49	2.08	12.57	0.85
Nylon	2	20.82	16.00	36.82	0.59
Nylon	3	31.47	29.72	61.19	0.54
Nylon	4	42.49	31.76	74.25	0.59
Nylon	5	52.98	31.42	84.4	0.65

4.4.3 Basalt BCR

Result Table 4.16 illustrates the fiber volume fraction in various layers of basalt material. The first layer has a fiber volume fraction of 0.48, signifying that fibers constitute about 48% of the material. The balanced composition of this layer is indicated by the moderate rope content and a significant amount of resin and rod. The second layer sees an increase in rope content, leading to a rise in the fiber volume fraction to 0.52. This layer is characterized by enhanced fiber reinforcement, which likely boosts its mechanical properties. Layer 3, on the other hand, has a lower fiber volume fraction of 0.46, possibly due to the higher resin and rod content.

In the fourth layer, a substantial increase in rope content results in the highest fiber volume fraction of 0.60. This layer showcases robust fiber reinforcement, which could potentially improve the material's strength. The fifth layer maintains a fairly high fiber volume fraction of 0.54, with the equilibrium between rope, resin, and rod components influencing the overall material properties.

To sum up, the performance of the basalt composite material hinges on the optimal balance of fiber content. Layers 2 and 4 display the highest fiber fractions, while layer 3 shows a slight

deviation. This data can guide designers in customizing material compositions for specific uses, taking into account both strength and cost-effectiveness.

Table 4.16 Fiber volume fraction in basalt BCR

Material	Layer	Rope g/lm	Resin g/lm	Rod g/lm	Fiber Volume Fraction
Basalt	1	19.73	10.56	53.5	0.48
Basalt	2	39.74	18.14	45.63	0.52
Basalt	3	58.57	33.49	57.18	0.46
Basalt	4	81.27	27.33	33.63	0.60
Basalt	5	93.97	39.23	41.75	0.54

4.4.4 Polypropylene & Basalt BCR

Table 4.17 presents the fiber volume fraction for different layers of the PP + Basalt composite material. The first layer has a fiber volume fraction of 0.60, suggesting that fibers make up about 60% of the material. The balanced composition of this layer is indicated by the moderate rope content and a substantial amount of resin and rod. The second layer sees an increase in rope content, leading to a slight decrease in the fiber volume fraction to 0.53. This layer maintains a good equilibrium between reinforcement and resin content. Layer 3 shows an enhanced fiber volume fraction of 0.56, which can be attributed to the higher rope and rod content.

Table 4.17 Fiber volume fraction in polypropylene + basalt BCR

Material	Layer	Rope g/lm	Resin g/lm	Rod g/lm	Fiber Volume Fraction
PP + Basalt	1	11.30	4.83	16.13	0.60
PP + Basalt	2	19.90	11.37	31.27	0.53
PP + Basalt	3	28.50	14.56	43.06	0.56
PP + Basalt	4	39.00	21.63	60.63	0.53
PP + Basalt	5	51.50	24.64	76.14	0.57

In the fourth layer, despite the continued increase in rope content, the fiber volume fraction remains steady at 0.53. This layer achieves a balance between reinforcement and matrix components. The fifth layer maintains a relatively high fiber volume fraction of 0.57, with the harmony between rope, resin, and rod components influencing the overall material properties.

Data Table 4.17 suggests here the performance of the PP + Basalt composite material is contingent on finding the optimal balance of fiber content. Layers 1 and 5 represent the

extremes, while layers 2, 3, and 4 find a middle ground. This information can guide designers in customizing material compositions for specific uses, taking into account both strength and cost-effectiveness.

4.4.5 Nylon & Basalt BCR

Table 4.18 illustrates the fiber volume fraction for different layers of the Nylon + Basalt composite material. The first layer has a fiber volume fraction of 0.49, suggesting that fibers constitute about 49% of the material. The balanced composition of this layer is indicated by the moderate rope content and a substantial amount of resin and rod. The second layer sees an increase in rope content, leading to a decrease in the fiber volume fraction to 0.43. This layer maintains a good equilibrium between reinforcement and resin content. Layer 3 shows an enhanced fiber volume fraction of 0.51, which can be attributed to the higher rope and rod content. In the fourth layer, despite the continued increase in rope content, the fiber volume fraction increases slightly to 0.52. This layer achieves a balance between reinforcement and matrix components. The fifth layer maintains a relatively high fiber volume fraction of 0.54, with the harmony between rope, resin, and rod components influencing the overall material properties.

Table 4.18 Fiber volume fraction in nylon + basalt BCR

Material	Layer	Rope g/lm	Resin g/lm	Rod g/lm	Fiber Volume Fraction
Nylon + Basalt	1	12.85	9.03	21.88	0.49
Nylon + Basalt	2	23.50	21.37	44.87	0.43
Nylon + Basalt	3	35.00	23.42	58.42	0.51
Nylon + Basalt	4	45.65	28.37	74.02	0.52
Nylon + Basalt	5	58.25	33.50	91.75	0.54

To sum up, it is observed from analysis fibre volume fraction analysis ranges between 40% - 65% which may help in increased load bearing capacity of prepared braided composite rods.

4.5 Tensile Properties of BCR

4.5.1 Comparison Between Layer

4.5.1.1 Polypropylene BCR

The data presented in Table 4.19 and Figure 4.17 offer a comprehensive view of the tensile properties of Polypropylene (PP) braided rods across five different layers. The initial layer features a rod diameter of 5.00 mm and an ultimate load capacity of 786.12 Kgf, which

increases with an increase in rod diameter leading maximum strength of 1889.88 Kgf of the fifth layer with 7.84 mm rod diameter, which is evident that as diameter increases the rod strength increases.

Looking at the stress value of PP braided composite rods, it is observed from Figure 4.17 that as the diameter increases the load-bearing capacity of the PP braided composite rod decreases, this can be attributed to a larger diameter, the outer layers bear more load compared to the inner layers.

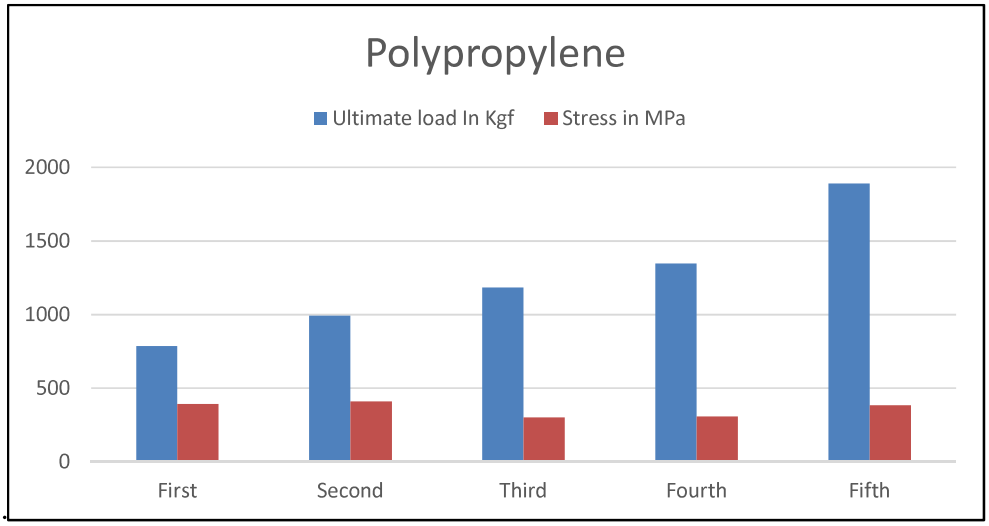


Figure 4.17 Comparison of ultimate load with stress

This uneven distribution can cause a reduction in the overall stress-bearing capacity of the rope as a composite structure. Apart from that larger diameter ropes experience higher shear forces between layers. These forces can cause slippage or deformation between layers, reducing the overall tensile strength. As seen from the figure 4.17, the stress value decreases from the first layer to the fourth layer but a sudden rise has been observed in the stress value for the fifth layer, this can be attributed to more concentric pressure as number of layer increases.

Figure 4.18 compares polypropylene braided rod for its strain percentage with modulus. The strain percentage is also crucial in steel rebars and braided composite rods. The strain percentage becomes more important for high-altitude buildings. The percentage strain of the prepared PP braided composite rods ranges from 21% to 31%, which is very well in the range defined by steel grade IS requirement of 10% to 23%. Apart from that modulus of the prepared rod also remains almost constant. This suggests that the material becomes stiffer and potentially more brittle with each successive layer, which could be a deliberate design choice to meet

specific mechanical requirements in applications where higher load-bearing capacity and stiffness are desired.

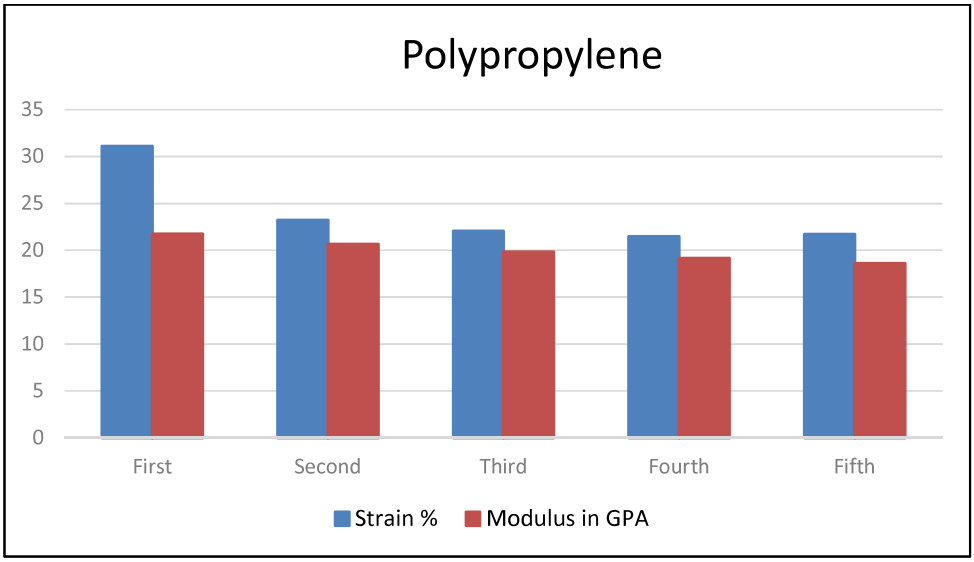


Figure 4.18 Comparison of strain % with modulus

(a) Marking before testing

(b) Sample mounting

Figure 4.19 Rod Tensile Testing Process

4.5.1.2 Nylon BCR

The data presented in Table 4.20 and Figure 4.20 offers a comprehensive view of the tensile properties of Nylon braided rods across five different layers. The initial layer features a rod

diameter of 4.25 mm and an ultimate load capacity of 1367.10 Kgf, which increases with an increase in rod diameter leading maximum strength of 2845.35 Kgf of the fifth layer with 9.17 mm rod diameter, which is evident that as diameter increases the rod strength increases.

Looking at the stress value of Nylon braided composite rods, it is observed from the figure 4.20 that as the diameter increases the load-bearing capacity of the Nylon braided composite rod decreases, this can be attributed to a larger diameter, the outer layers bear more load compared to the inner layers.

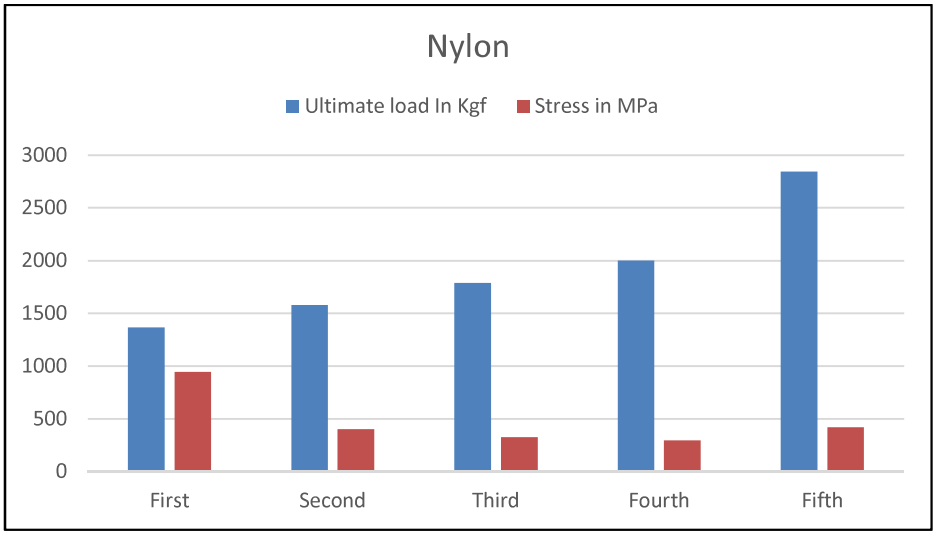


Figure 4.20 Comparison of ultimate load with stress

In braided structures, the angle at which fibers are interwoven (braiding angle) influences the mechanical properties. As the diameter increases, the braiding angle often changes, leading to less optimal fiber alignment for bearing axial loads. This uneven distribution can cause a reduction in the overall stress-bearing capacity of the rope as a composite structure. Apart from that larger diameter ropes experience higher shear forces between layers. These forces can cause slippage or deformation between layers, reducing the overall tensile strength. As seen from the Figure 4.20, the stress value decreases from the first layer to the fourth layer but a rise has been observed in the stress value for the fifth layer, this can be attributed to more concentric pressure as number of layer increases.

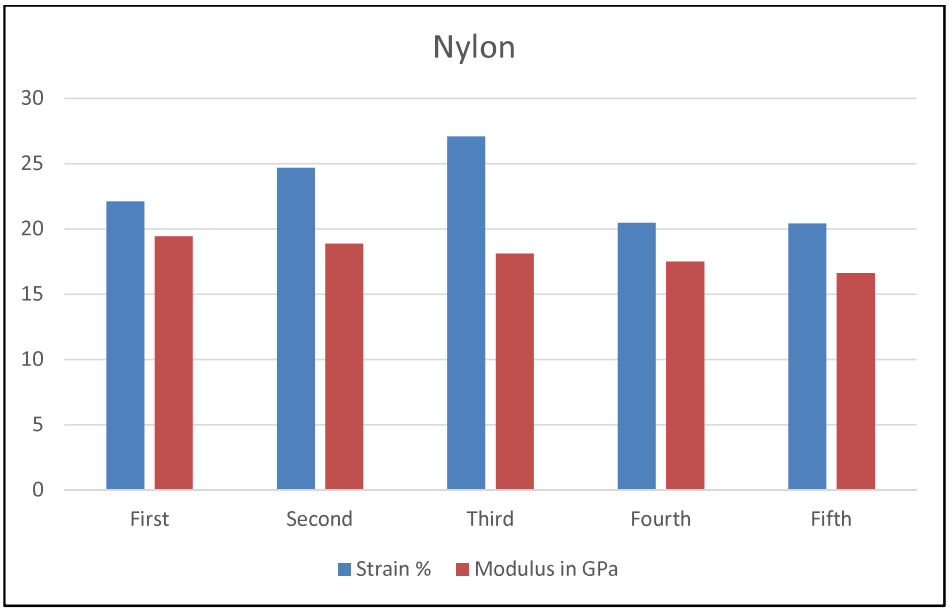


Figure 4.21 Comparison of strain % with modulus

Figure 4.21 compares nylon braided rod for its strain % with modulus. The strain percentage is also crucial in steel rebars and braided composite rods. The strain percentage becomes more important for high-altitude buildings. The percentage strain of the prepared nylon braided composite rods ranges from 16% to 19%, which is very well in the range defined by steel grade IS requirement of 10% to 23%. Apart from that modulus of the prepared rod also remains almost constant. This suggests that the material becomes stiffer and potentially more brittle with each successive layer, which could be a deliberate design choice to meet specific mechanical requirements in applications where higher load-bearing capacity and stiffness are desired.

4.5.1.3 Basalt BCR

The data presented in Figure 4.22 offers a comprehensive view of the tensile properties of Basalt braided rods across five different layers. The initial layer features a rod diameter of 4.50 mm and an ultimate load capacity of 1087.32 Kgf, which increases with an increase in rod diameter leading to a maximum strength of 2856.24 Kgf of the fifth layer with 9.10 mm rod diameter, which is evident that as diameter increases the rod strength increases.

Looking at the stress value of Basalt braided composite rods, it is observed from the Table 4.21 and Figure 4.23 that as the diameter increases the load-bearing capacity of the Basalt braided composite rod decreases as the effective tensile force that each fiber can carry is reduced due to less optimal alignment and increased structural imperfections as diameter increases. In

braided structures, the angle at which fibers are interwoven (braiding angle) influences the mechanical properties. This uneven distribution can cause a reduction in the overall stress-bearing capacity of the rope as a composite structure. Apart from that larger diameter ropes experience higher shear forces between layers. These forces can cause slippage or deformation between layers, reducing the overall tensile strength. As seen from the Figure 4.22, the stress value decreases from the first layer to the fourth layer but a rise has been observed in the stress value for the fifth layer, this can be attributed to more concentric pressure as number of layer increases.

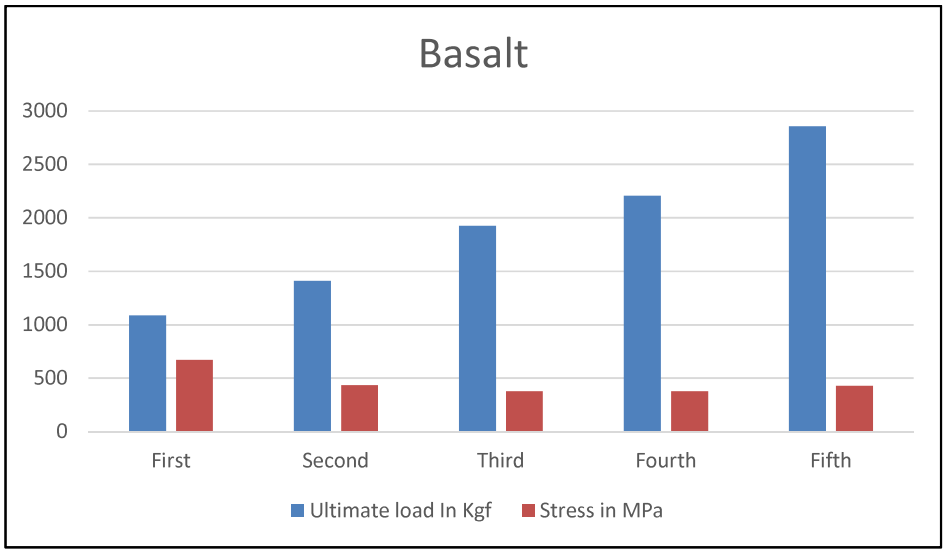


Figure 4.22 Comparison of ultimate load with stress

The strain percentage is also crucial in steel rebars and braided composite rods. The strain percentage becomes more important for high-altitude buildings. Figure 4.23 compares basalt braided rod for its tensile properties, i.e. strain % with modulus. The percentage strain of the prepared Basalt braided composite rods ranges from 9% to 16%, which is very well in the range defined by steel grade IS requirement of 10% to 23%. The data suggests that as the rod diameter increases, the material can withstand greater loads while exhibiting more significant deformation before failure. This balance of properties could be beneficial in scenarios where Basalt rods are subjected to dynamic loads or need to absorb energy without failing.

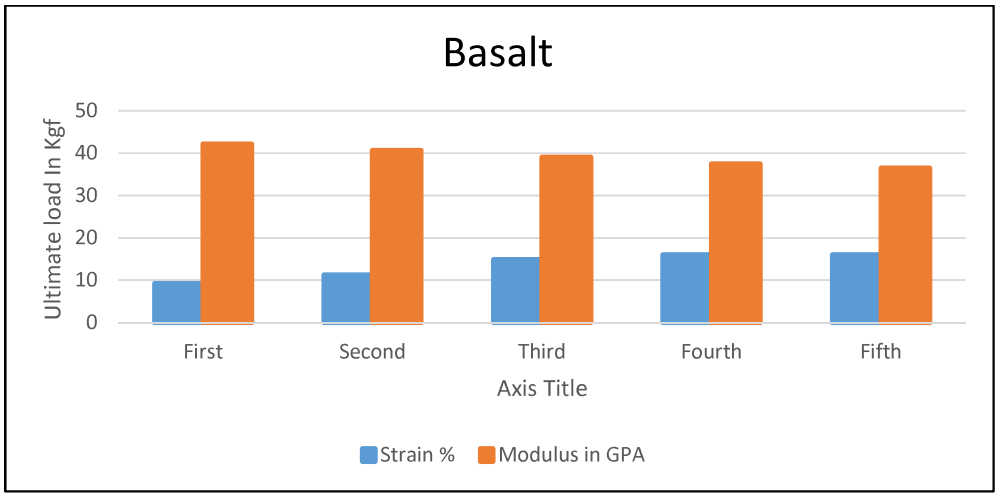


Figure 4.23 Comparison of strain % with modulus

4.5.1.4 PP + Basalt

The data presented in Figure 4.24 offers a comprehensive view of the tensile properties of PP + Basalt braided rods across five different layers. The initial layer features a rod diameter of 4.00 mm and an ultimate load capacity of 960.04 Kgf, which increases with an increase in rod diameter leading to a maximum strength of 1751.89 Kgf of the fifth layer with 8.03 mm rod diameter, which is evident that as diameter increases the rod strength increases.

Looking at the stress value of PP + Basalt braided composite rods, it is observed from the Table 4.22 and Figure 4.20 that as the diameter increases the load-bearing capacity of the PP + Basalt braided composite rod decreases, this can be attributed to a larger diameter, the outer layers bear more load compared to the inner layers. This uneven distribution can cause a reduction in the overall stress-bearing capacity of the rope as a composite structure.

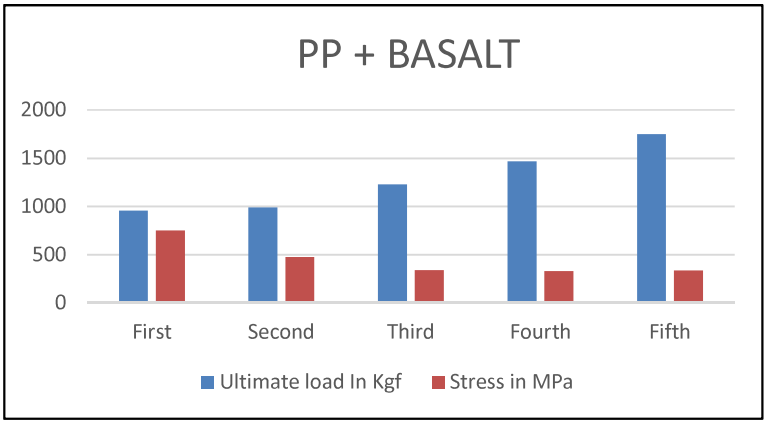


Figure 4.24 Comparison of ultimate load with stress

Apart from that larger diameter ropes experience higher shear forces between layers. These forces can cause slippage or deformation between layers, reducing the overall tensile strength. As seen from the figure 4.20, the stress value decreases from the first layer to the fourth layer but a sudden rise has been observed in the stress value for the fifth layer, this can be attributed to more concentric pressure as number of layer increases.

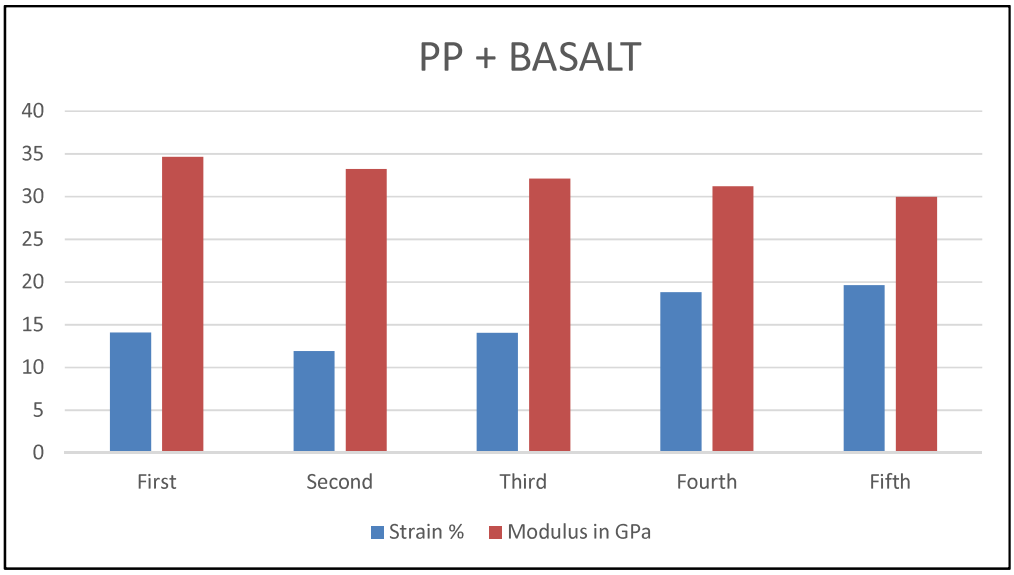


Figure 4.25 Comparison of strain % with modulus

The strain percentage is also crucial in steel rebars and braided composite rods. The strain percentage becomes more important for high-altitude buildings. As shown in Figure 4.25, the percentage strain of the prepared PP + Basalt braided composite rods ranges from 14% to 20%, which is very well in the range defined by steel grade IS requirement of 10% to 23%. Apart from that modulus of the prepared rod also remains almost constant. The data suggests that as the rod diameter increases, the material can withstand greater loads while exhibiting more significant deformation before failure. This balance of properties could be beneficial in scenarios where Basalt rods are subjected to dynamic loads or need to absorb energy without failing.

4.5.1.5 Nylon + Basalt

The data presented in Figure 4.26 offers a comprehensive view of the tensile properties of Nylon + Basalt braided rods across five different layers. The initial layer features a rod diameter of 4.00 mm and an ultimate load capacity of 1196.35 Kgf, which increases with an increase in rod diameter leading maximum strength of 2869.29 Kgf of the fifth layer with 8.75 mm rod diameter, which is evident that as diameter increases the rod strength increases.

Looking at the stress value of Nylon + Basalt braided composite rods, it is observed from the Table 4.23 and Figure 4.26 that as the diameter increases the load-bearing capacity of the Nylon + Basalt braided composite rod decreases, this can be attributed to a larger diameter, the outer layers bear more load compared to the inner layers.

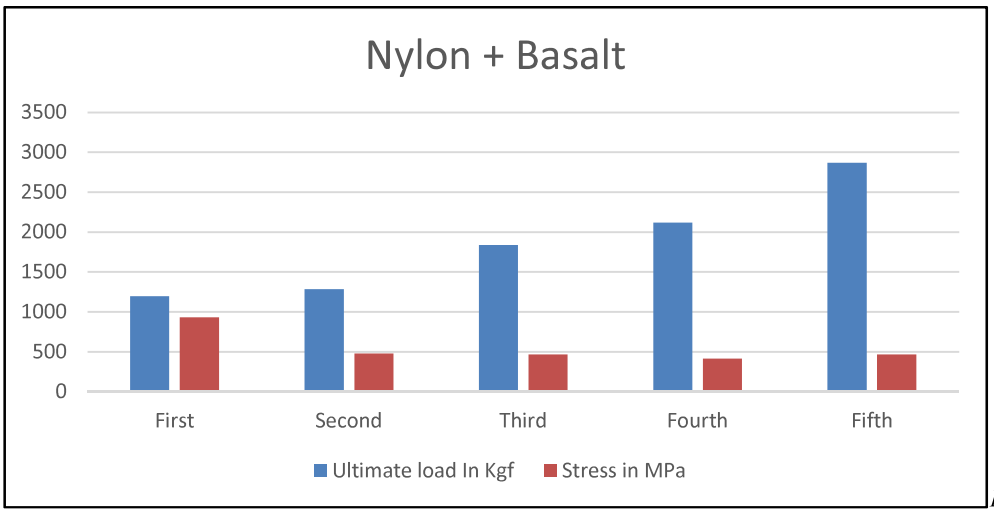


Figure 4.26

Comparison of ultimate load with stress

In braided structures, the angle at which fibers are interwoven (braiding angle) influences the mechanical properties. As the diameter increases, the braiding angle often changes, leading to less optimal fiber alignment for bearing axial loads. This uneven distribution can cause a reduction in the overall stress-bearing capacity of the rope as a composite structure. Apart from that larger diameter ropes experience higher shear forces between layers. These forces can cause slippage or deformation between layers, reducing the overall tensile strength. As seen from Figure 4.26, the stress value decreases from the first layer to the fourth layer but a sudden rise has been observed in the stress value for the fifth layer, this can be attributed to more concentric pressure as the number of layers increases.

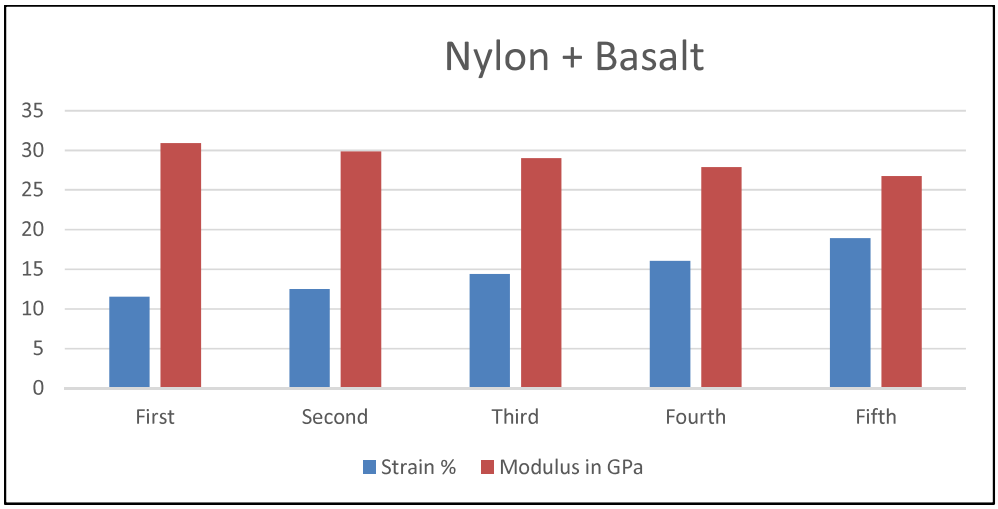


Figure 4.27 Comparison of strain % with modulus

The strain percentage is also crucial in steel rebars and braided composite rods. The strain percentage becomes more important for high-altitude buildings. Figure 4.27 the percentage strain of the prepared Nylon + Basalt braided composite rods ranges from 11% to 19%, which is very well in the range defined by steel grade IS requirement of 10% to 23%. Apart from that modulus of the prepared rod also remains almost constant. This suggests that the material becomes stiffer and potentially more brittle with each successive layer, which could be a deliberate design choice to meet specific mechanical requirements in applications where higher load-bearing capacity and stiffness are desired.

4.5.2 Comparison within Layer

In this section, we have tried to compare the mechanical properties of prepared braided composite rods made from different raw materials, layer wise. The objective of this comparison is to made a decision on which type of material to be used as per requirement.

4.5.2.1 First layer

The tensile test results for the first layer of braided rods made from different materials reveal significant variations in performance (Figure 4.24). Polypropylene (PP), with a rod diameter of 5.00 mm, exhibited an ultimate load of 786.12 Kgf and a stress of 392.96 MPa. Notably, it had the highest strain percentage at 31.09%, indicating a higher degree of elasticity, but a lower modulus of 21.74 GPa, suggesting less stiffness compared to other materials.

Nylon, with a smaller diameter of 4.25 mm, showed a much higher ultimate load capacity of 1367.10 Kgf and stress of 945.85 MPa, reflecting its superior strength. However, its strain

percentage was lower at 22.12%, and the modulus was 19.44 GPa, indicating that while it is stronger, it is also less stiff than PP. Basalt rods, measuring 4.50 mm in diameter, presented an ultimate load of 1087.32 Kgf and a stress of 671.01 MPa. Its strain percentage was the lowest at 9.16%, which correlates with the highest modulus of 42.09 GPa, signifying that basalt is the stiffest material among those tested.

The composite materials, PP + Basalt (35:65) and Nylon + Basalt (50:50), both with diameters of 4.00 mm, demonstrated interesting properties. The PP and Basalt composite bore an ultimate load of 960.04 Kgf and a stress of 749.84 MPa, with a strain percentage of 14.10% and a modulus of 34.65 GPa. This suggests a balanced compromise between elasticity and stiffness. The Nylon and Basalt composite carried an ultimate load of 1196.35 Kgf and a stress of 934.41 MPa, with a strain percentage of 11.56% and a modulus of 30.95 GPa, indicating a material that is both strong and relatively stiff.

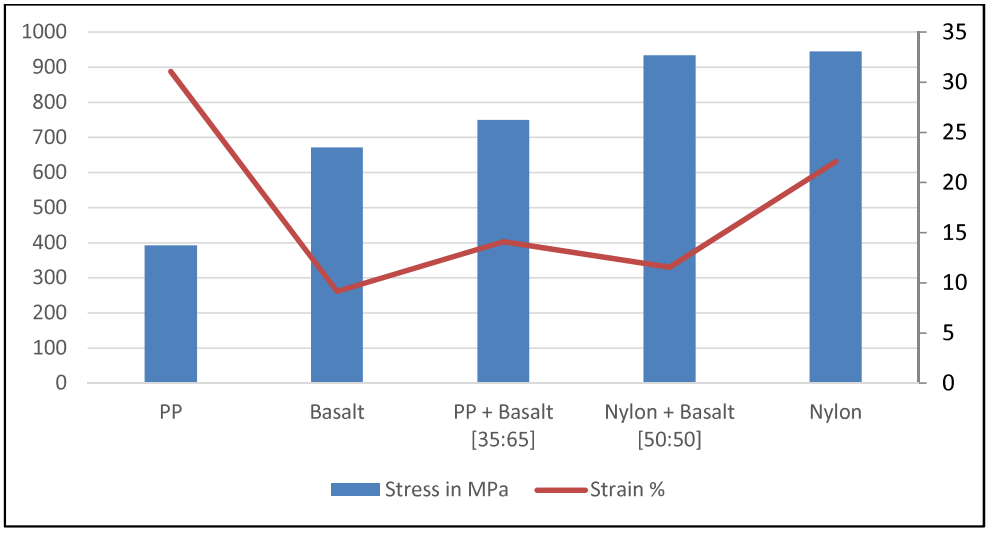


Figure 4.28 First layer braided rod tensile properties comparison

This change in load bearing capacity of braided composite rod of first layer is due to the change in the reinforcement material. Here, different variety of yarn which differ in their tensile properties are used as reinforcement material, which is responsible for change in load bearing capacity. Apart from that, variation in fibre volume fraction also affects the strength of braided ropes.

It is also observed from Figure 4.28, that strain behavior of braided composite rod is completely inverse than its stress value. In the case of less stress the extension percentage increases and vice-versa.

4.5.2.2 Second layer

The tensile test results for the second layer of braided rods shown in Figure 4.29, shows a diverse range of mechanical properties across different materials. For Polypropylene (PP), the rod diameter increased to 5.50 mm from the first layer, and correspondingly, the ultimate load also increased to 994.22 Kgf. The stress experienced by PP is 410.73 MPa, and the strain percentage decreased to 23.21%, indicating less elasticity than the first layer. The modulus of elasticity slightly decreased to 20.65 GPa, suggesting a minor reduction in stiffness. Nylon rods, with a significant increase in diameter to 7.00 mm, showed an increased ultimate load of 1581.44 Kgf. Interestingly, the stress decreased to 403.33 MPa, and the strain percentage increased to 24.70%, indicating that the second layer of Nylon is less strong but more elastic than the first layer.

The modulus of elasticity also decreased to 18.89 GPa, pointing to a decrease in stiffness. For Basalt, the diameter increased to 6.35 mm, and the ultimate load reached 1410.74 Kgf. The stress for Basalt increased to 437.22 MPa, and the strain percentage slightly increased to 11.22%, while the modulus of elasticity decreased to 40.63 GPa. These changes suggest that the second layer of Basalt is stronger but slightly less stiff than the first layer.

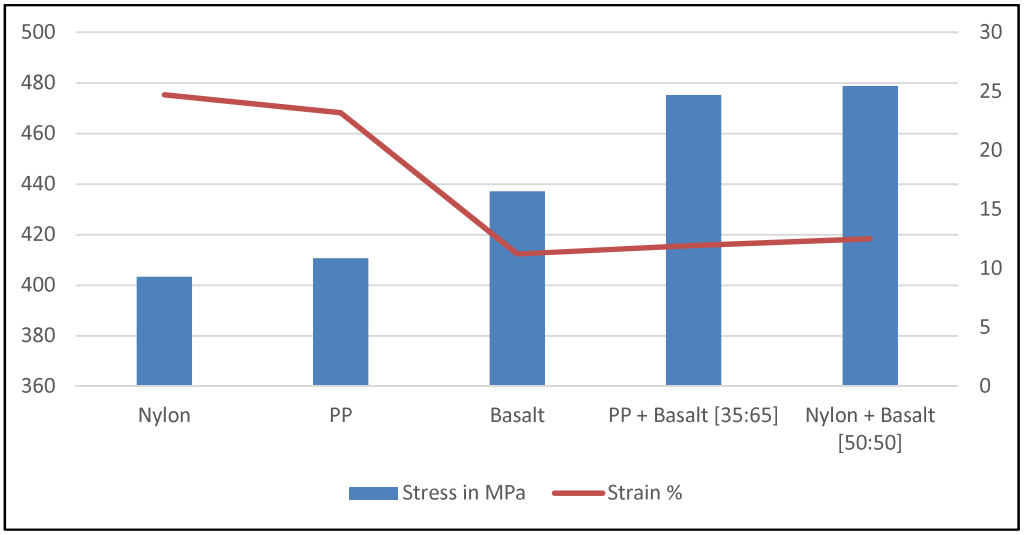


Figure 4.29 Second layer braided rod tensile properties comparison

The composite material PP + Basalt (35:65) saw a slight increase in rod diameter to 5.10 mm and a corresponding increase in ultimate load to 989.22 Kgf. The stress significantly increased to 475.28 MPa, and the strain percentage rose to 11.94%, with a decrease in the modulus of elasticity to 33.26 GPa. This indicates that the second layer of this composite is stronger and

more elastic but less stiff than the first layer. Lastly, the Nylon + Basalt (50:50) composite, with a diameter of 5.80 mm, showed an ultimate load of 1288.75 Kgf. The stress slightly increased to 478.75 MPa, and the strain percentage rose to 12.52%. The modulus of elasticity decreased to 29.88 GPa, suggesting that the second layer is stronger, more elastic, and less stiff than the first layer.

This change in load bearing capacity of braided composite rod of second layer is due to the change in the reinforcement material. Here, different variety of yarn which differ in their tensile properties are used as reinforcement material, which is responsible for change in load bearing capacity. Apart from that, variation in fibre volume fraction also affects the strength of braided ropes.

It is also observed from Figure 4.25, that strain behavior of braided composite rod is completely inverse than its stress value. In the case of less stress the extension percentage increases and vice-versa.

4.5.2.3 Third layer

The data from figure 4.30, reflects the tensile properties of the third layer of braided rods, revealing how different materials respond under tension. The polypropylene (PP) rod diameter is now 7.00 mm, and the ultimate load it can bear is 1186.14 Kgf. The stress experienced by PP is 302.51 MPa, with a strain percentage of 22.03%. The modulus of elasticity is 19.83 GPa, indicating that the material is quite resilient, maintaining a high strain percentage while the stress has decreased compared to the second layer. Nylon With a larger diameter of 8.25 mm, the ultimate load for Nylon increases to 1787.80 Kgf. The stress is 328.25 MPa, and the strain percentage is 27.10%, the highest among the materials, suggesting Nylon is the most elastic. The modulus of elasticity is 18.14 GPa, showing a decrease in stiffness, which correlates with the increased elasticity. Basalt rod diameter is 8.00 mm, and it has an ultimate load of 1928.23 Kgf, the highest among the materials. The stress is 376.51 MPa, and the strain percentage is 14.89%. The modulus of elasticity is a high 39.01 GPa, indicating Basalt's superior stiffness and strength.

PP + Basalt (35:65) composite material has a rod diameter of 6.70 mm and an ultimate load of 1230.84 Kgf. The stress is 342.65 MPa, and the strain percentage is 14.06%. The modulus of elasticity is 32.11 GPa, which suggests that the composite has good strength and stiffness, benefiting from the properties of both PP and Basalt. Nylon + Basalt (50:50) with a rod

diameter of 7.00 mm, this composite bears an ultimate load of 1838.89 Kgf. The stress is 468.99 MPa, the highest recorded stress, and the strain percentage is 14.42%. The modulus of elasticity is 29.04 GPa, indicating that this composite is strong and has a reasonable level of stiffness, likely due to the balanced contribution of Nylon and Basalt.

This change in load bearing capacity of braided composite rod of third layer is due to the change in the reinforcement material. Here, different variety of yarn which differ in their tensile properties are used as reinforcement material, which is responsible for change in load bearing capacity. Apart from that, variation in fibre volume fraction also affects the strength of braided ropes.

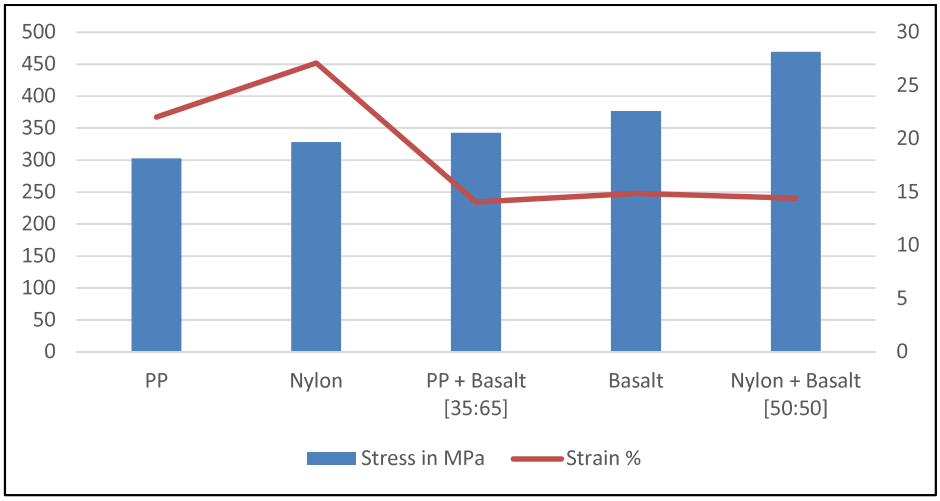


Figure 4.30 Third layer braided rod tensile properties comparison

It is also observed from Figure 4.30, that strain behavior of braided composite rod is completely inverse than its stress value. In the case of less stress the extension percentage increases and vice-versa.

4.5.2.4 Fourth layer

The data presented in Figure 4.31 provides insights into the tensile properties of various materials in the fourth layer of braided rods. Here's a detailed analysis Polypropylene (PP) rod diameter has slightly increased to 7.38 mm compared to the third layer. It can withstand an ultimate load of 1347.87 Kgf, which is higher than the previous layer. The stress it experiences is 309.27 MPa, and the strain percentage is 21.46%, indicating a slight decrease in elasticity with a modulus of 19.14 GPa, suggesting a minor reduction in resilience. The rod diameter for

Nylon is now 9.19 mm, and it can bear an ultimate load of 2000.98 Kgf. The stress is 296.08 MPa, which is lower than the third layer, and the strain percentage is 20.48%, showing a slight decrease in elasticity. The modulus of elasticity is 17.51 GPa, indicating a decrease in stiffness, which aligns with the increased diameter and load-bearing capacity.

With a rod diameter of 8.54 mm, Basalt can handle an ultimate load of 2209.05 Kgf, the highest among the materials. The stress is 378.52 MPa, and the strain percentage is 15.98%. The modulus of elasticity is 37.45 GPa, which is slightly lower than the third layer, yet it still reflects Basalt's significant stiffness and strength.

PP + Basalt (35:65) composite has a rod diameter of 7.46 mm and an ultimate load of 1468.90 Kgf. The stress is 329.85 MPa, and the strain percentage is 18.83%. The modulus of elasticity is 31.21 GPa, showing that the composite maintains good stiffness and strength, with a slight increase in stress and a decrease in strain percentage compared to the third layer. Nylon + Basalt (50:50) rod diameter for this composite is 7.99 mm, and it can withstand an ultimate load of 2119.73 Kgf. The stress is 414.94 MPa, the highest among the materials, and the strain percentage is 16.07%. The modulus of elasticity is 27.88 GPa, indicating that this composite has a high level of strength and a moderate level of stiffness, likely due to the balanced contribution of Nylon and Basalt.

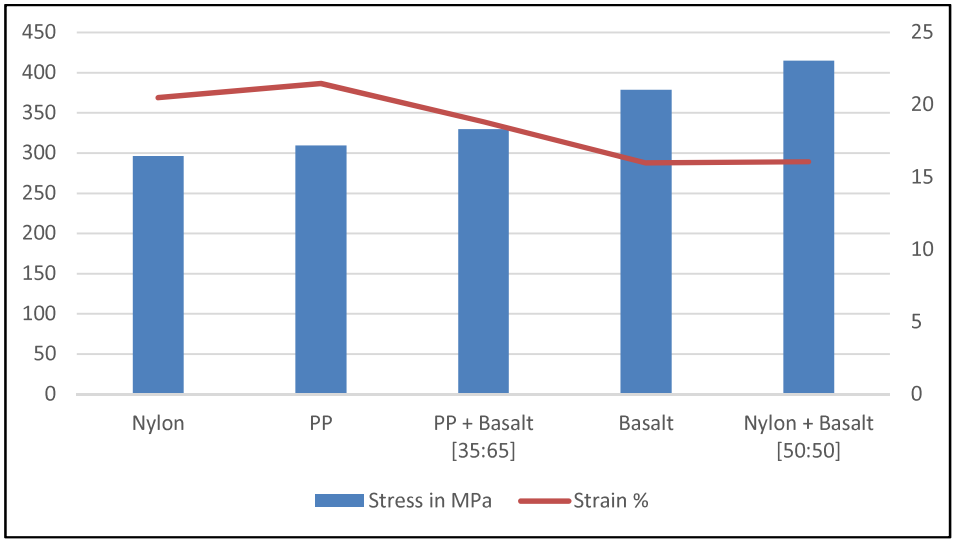


Figure 4.31 Fourth layer braided rod tensile properties comparison

This change in load bearing capacity of braided composite rod of fourth layer is due to the change in the reinforcement material. Here, different variety of yarn which differ in their tensile

properties are used as reinforcement material, which is responsible for change in load bearing capacity. Apart from that, variation in fibre volume fraction also affects the strength of braided ropes.

It is also observed from Figure 4.31, that strain behavior of braided composite rod is completely inverse than its stress value. In the case of less stress the extension percentage increases and vice-versa.

4.5.2.5 Fifth layer

The data in Table 4.28 & figure 4.32 reflects the tensile properties of various materials in the fifth layer of braided rods, indicating a progression in mechanical characteristics from the fourth layer. Polypropylene (PP) Exhibits an increase in rod diameter to 7.84 mm and a significant rise in ultimate load capacity to 1889.88 Kgf. The stress experienced by PP is 384.24 MPa, with a strain percentage of 21.71%, suggesting enhanced strength while maintaining a high level of elasticity. The modulus of elasticity is 18.60 GPa, indicating a slight improvement in material stiffness. Nylon With a rod diameter of 9.17 mm, shows a remarkable increase in ultimate load to 2845.35 Kgf. The stress it can endure is 422.86 MPa, and the strain percentage is 20.43%, demonstrating a balance between strength and flexibility. The modulus of elasticity is 16.63 GPa, slightly lower than the fourth layer, which may be attributed to the material's increased load-bearing capacity. The rod diameter slightly decreases to 9.10 mm, yet Basalt's ultimate load capacity is the highest at 2856.24 Kgf. It endures a stress of 431.03 MPa and has a strain percentage of 16.02%. The modulus of elasticity is 36.40 GPa, reflecting Basalt's superior stiffness and strength among the materials tested.

PP + Basalt (35:65) composite's rod diameter is 8.03 mm, with an ultimate load of 1751.89 Kgf. It experiences a stress of 339.53 MPa and a strain percentage of 19.65%. The modulus of elasticity is 29.96 GPa, indicating that the composite benefits from the combined properties of PP and Basalt, resulting in a material that is strong yet less stiff than pure Basalt. Nylon + Basalt (50:50) rod diameter for this composite is 8.75 mm, and it can withstand an ultimate load of 2869.29 Kgf, the highest among the composites. It experiences a stress of 468.34 MPa and a strain percentage of 18.96%. The modulus of elasticity is 26.76 GPa, showcasing a composite that is exceptionally strong and moderately stiff, likely due to the synergistic effect of Nylon and Basalt.

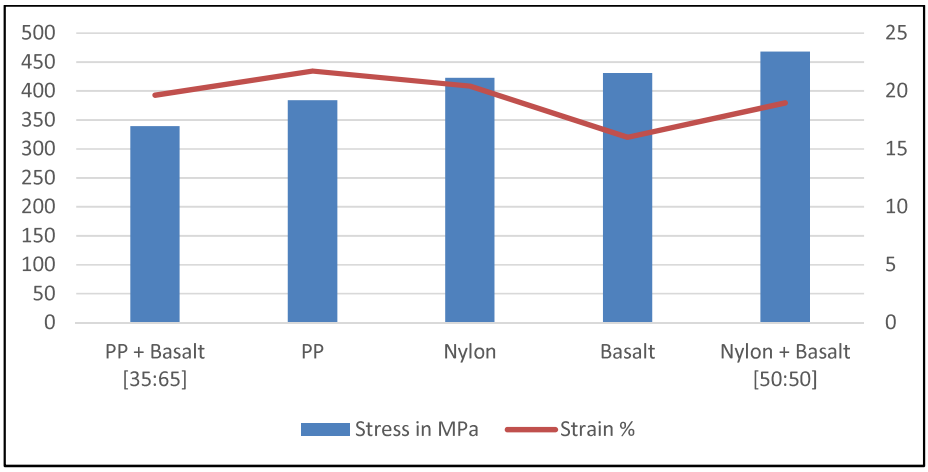


Figure 4.32 Fifth layer braided rod tensile properties comparison

This change in load bearing capacity of braided composite rod of fifth layer is due to the change in the reinforcement material. Here, different variety of yarn which differ in their tensile properties are used as reinforcement material, which is responsible for change in load bearing capacity. Apart from that, variation in fibre volume fraction also affects the strength of braided ropes.

It is also observed from Figure 4.32, that strain behavior of braided composite rod is completely inverse than its stress value. In the case of less stress the extension percentage increases and vice-versa.

4.6 Bond Strength of BCR by Pull Out

4.6.1 Polypropylene BCR

The Figure 4.33 presents a comparison of polypropylene braided rebar's (FRP bars) with steel rebar's in terms of their performance in a pullout test within a concrete block, which is a measure of bond strength. The polypropylene rebar's evaluated at two different layers, layer 4 and layer 5, with rod diameters of 7.38 mm and 7.84 mm respectively. The ultimate load capacity of the polypropylene rebar's is significantly higher than that of the steel rebar, with the fourth layer polypropylene rebar handling 441.30 kN and the fifth layer handling 506.11 kN, compared to the steel rebar's 357.16 kN. Similarly, the ultimate stress for polypropylene rebar's is greater, with the fourth layer at 176.79 MPa and the fifth layer at 198.77 MPa, versus the steel rebar's 141.36 MPa.

The superior performance of the Polypropylene BCR bars suggests that they provide better bonding and load transfer characteristics within the concrete block compared to steel rebar.

This makes Polypropylene FRP bars a highly effective reinforcement material, potentially offering significant advantages in applications requiring high pullout resistance and stress endurance in concrete structures. The noticeable difference in performance between the 4-layer and 5-layer Polypropylene FRP bars also highlights the importance of optimizing the layering to achieve maximum efficacy.

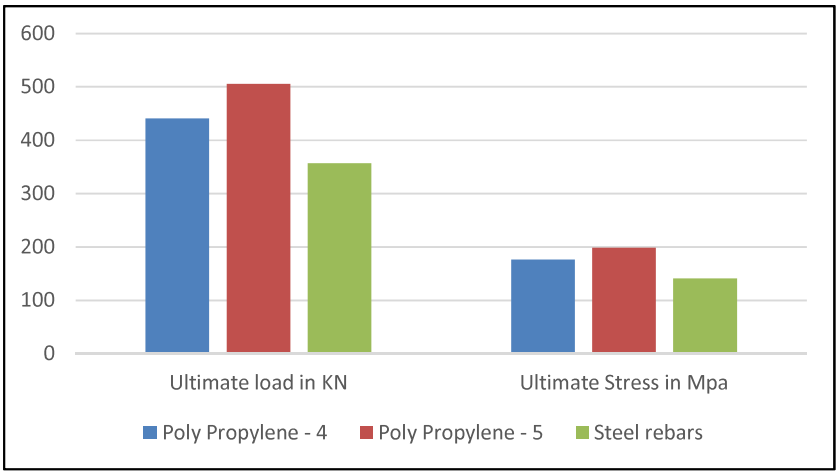


Figure 4.33 Comparison of BCR and steel rebar for bond strength

4.6.2 Nylon BCR

Figure 4.34 present a comparison between Nylon braided rebars (BCR bars) and traditional steel rebars in terms of their performance in a concrete block pullout test, which evaluates bond strength. The Nylon rebars are tested at two different layers, layer 4 and layer 5, with rod diameters of 9.19 mm and 9.17 mm respectively.

The ultimate load capacity of the Nylon rebars is lower than that of the steel rebar, with the fourth layer Nylon rebar handling 227.06 kN and the fifth layer handling 328.73 kN, compared to the steel rebar's 357.16 kN. However, the ultimate stress for Nylon rebars is comparable to that of the steel rebar, with the fourth layer at 99.68 MPa and the fifth layer at 143.68 MPa, versus the steel rebar's 141.36 MPa. The decrease in load-bearing capacity of Nylon rebars could be due to slippage between the layers and slippage between prepared rod and concrete material. As the prepared rods are from Nylon material changes of slippage is more due to surface characteristics of Nylon material. Better results with fifth layers may be due to more surface area available for bonding.

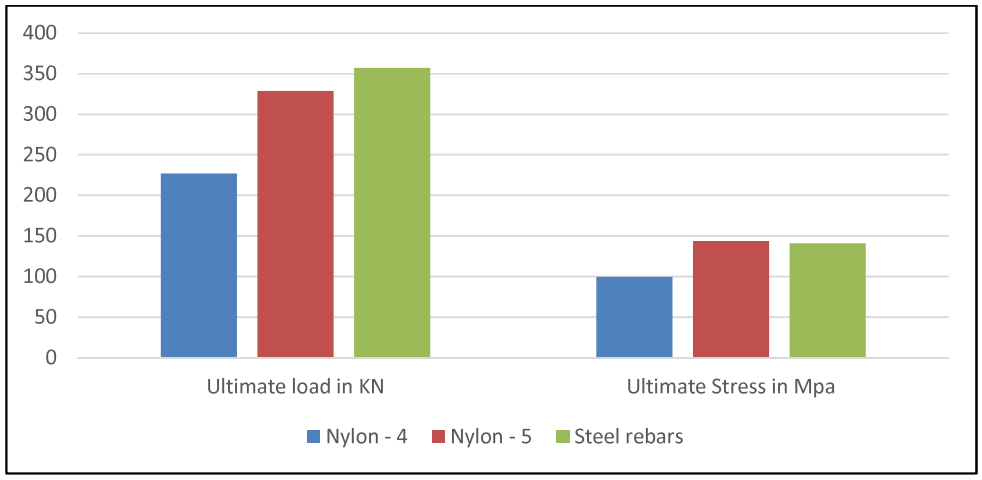


Figure 4.34 Comparison of BCR and steel rebar for bond strength

4.6.3 Basalt BCR

Figure 4.35 presents a comparison of the performance of basalt braided rebars and traditional steel rebars in terms of concrete bond strength. The data indicates that basalt rebars, with layers 4 and 5, have rod diameters of 8.53 mm and 9.1 mm, respectively. The ultimate load capacity for Basalt fourth layer is 404.82 kN, which is significantly higher than the 357.16 kN for steel rebars, despite the steel having a slightly smaller diameter of 8.35 mm. Correspondingly, the ultimate stress for Basalt fourth layer is 162.15 MPa, surpassing the steel's 141.36 MPa.

The Basalt fifth layer rebar, while having a larger diameter than the steel rebar, shows a lower ultimate load of 349.77 kN and ultimate stress of 150.78 MPa. This suggests that while the basalt rebars generally outperform steel in load capacity and stress, the performance can vary with the layering of the material.

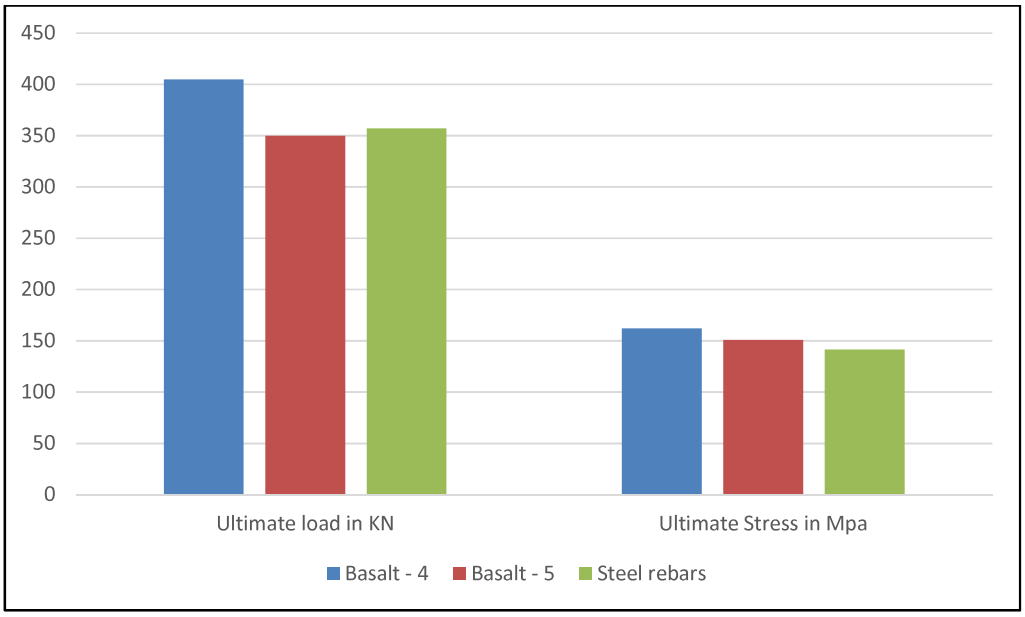


Figure 4.35 Comparison of BCR and steel rebar for bond strength

The superior performance of the fourth layer Basalt BCR suggests that they provide better bonding and load transfer characteristics within the concrete block compared to the steel rebars, making them a potentially more effective reinforcement material in concrete structures. However, the performance difference between the Basalt BCR configurations highlights the importance of optimizing the layering and diameter for maximum efficacy.

(a) Curing of samples

(c) Sample ready for test

(c) Sample mounting

(d) Sample after test

Figure 4.36 Process of Pull Out Test

4.6.4 PP + Basalt BCR

Figure 4.37 provide a comparative analysis of PP + Basalt braided rebars against traditional steel rebar, focusing on their bond strength within a concrete block as determined by a pullout test. The table lists two different layers for the PP + Basalt rebars, layer 4 with a rod diameter of 7.46 mm and layer 5 with a diameter of 8.03 mm. The ultimate load capacity of the PP + Basalt rebars is notably higher than that of the steel rebar, with fourth layer capable of withstanding 465.38 KN and fifth layer managing 427.22 KN, compared to the steel rebar's 357.16 KN. Furthermore, the ultimate stress for the PP + Basalt rebars is also higher, with layer 4 at 185.48 MPa and layer 5 at 167.6 MPa, versus the steel rebar's 141.36 MPa. . Overall, the PP + Basalt BCR demonstrate significant potential as an alternative to traditional steel rebars in concrete reinforcement applications.

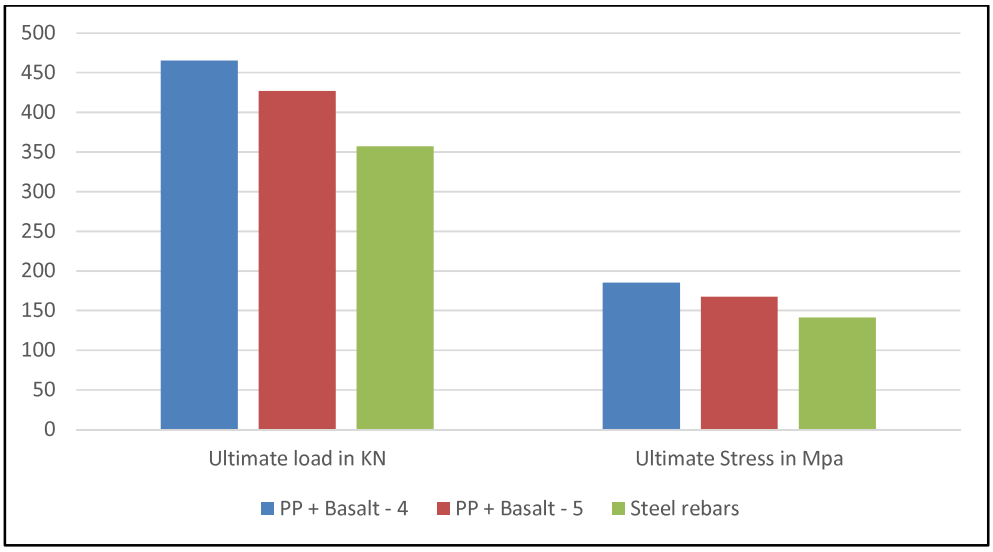


Figure 4.37 Comparison of BCR and steel rebar for bond strength

4.6.5 Nylon + basalt BCR

The data in Figure 4.38 compares the concrete bond strength of Nylon + Basalt braided rebars to traditional steel rebars. The Nylon + Basalt fourth rebars, with a diameter of 7.98 mm, exhibit an ultimate load of 378.82 kN and an ultimate stress of 148.60 MPa. These values are higher than those of steel rebars, which have a slightly larger diameter of 8.35 mm but a lower ultimate load and stress of 357.16 kN and 141.36 MPa, respectively. On the other hand, Nylon + Basalt fifth rebars, with a diameter of 8.75 mm, show a decrease in performance with an ultimate load of 313.48 kN and an ultimate stress of 128.20 MPa. This is below the performance of both Nylon + Basalt fourth layer rebars and steel rebars, indicating that the addition of nylon and the change in layering affect the bond strength.

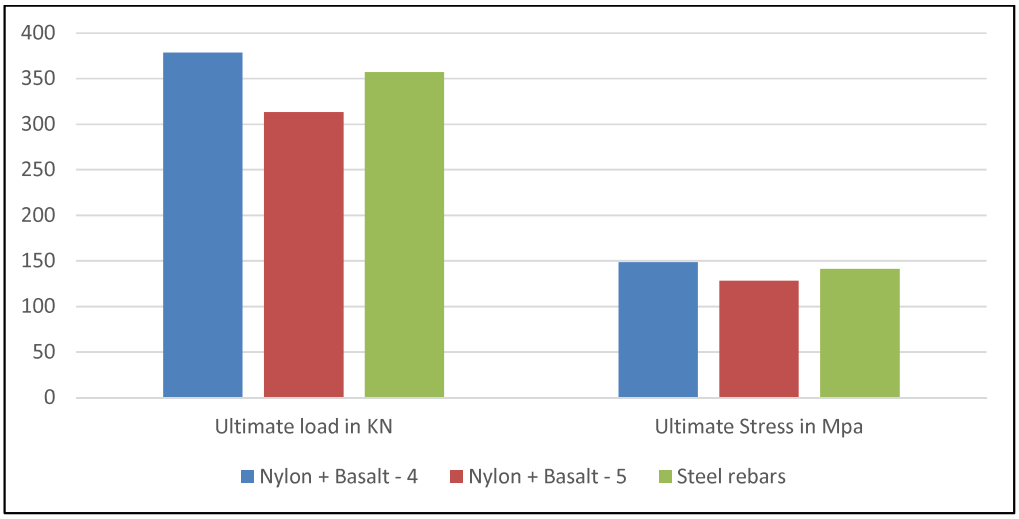


Figure 4.38 Comparison of BCR and steel rebar for bond strength

In the context of BCR pullout tests within a concrete block, these results suggest that the combination of nylon with basalt fibers can enhance the bond strength compared to traditional steel rebars, as evidenced by the Nylon + Basalt fourth layer rebars. However, the performance is dependent on the specific layering and material composition, as seen with the Nylon + Basalt fifth layer rebars. This highlights the importance of material selection and engineering design in optimizing the bond strength for BCRs in concrete applications, ensuring the structural integrity and longevity of the construction.

4.7 Flexural Strength of BCR

Flexural strength is one measure of the tensile strength of concrete. It is a measure of an unreinforced concrete beam or slab to resist failure in bending. High flexural strength is essential for stress-bearing restorations in later stages for height increment of a building. The more strength a material offers, the more units a restoration can include. High flexural strength also benefits the thickness of the restoration walls. A high-strength material allows a low wall thickness. As per IS standards, flexural strength should be in the range of 3.43 to 6.20 Mpa

(a) sample testing

(b) Sample preparation

Figure 4.39 Flexural Strength Testing

4.7.1 Polypropylene BCR

Table 4.34 & Figure 4.40 present a comparison of the flexural strength of concrete beams reinforced with Polypropylene braided rebars against those that are unreinforced. The data indicates that the reinforced beams exhibit significantly higher flexural strength, with the Polypropylene fourth layer showing a strength of 5.48 MPa and the Polypropylene fifth layer showing 5.79 MPa. In contrast, the unreinforced beam has a flexural strength of only 3.22 MPa. This translates to an increase in flexural strength of approximately 69.91% for the Polypropylene fourth layer and 79.27% for the Polypropylene fifth layer compared to the unreinforced beam.

These results underscore the effectiveness of Braided FRP Re-bars in enhancing the flexural strength of concrete beams, which could lead to more resilient structures capable of withstanding greater stress and load as per IS standards and could be a valuable strategy in the construction industry, particularly in applications where increased flexural strength is a critical factor.

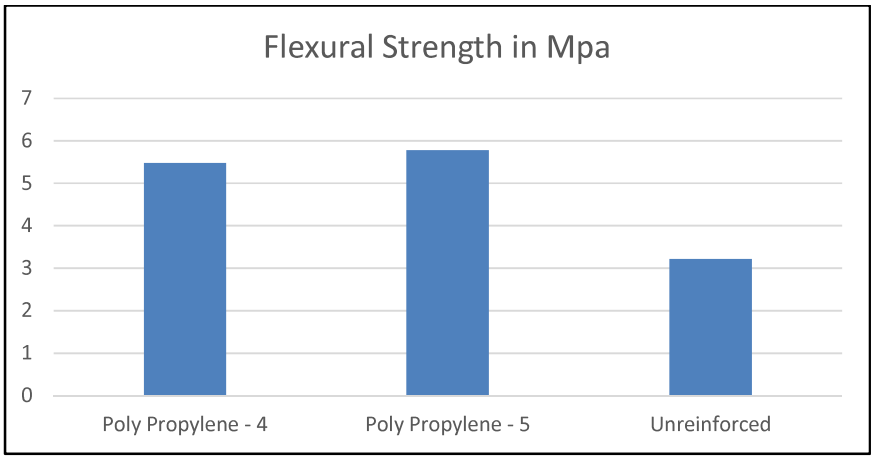


Figure 4.40 Comparison of BCR with unreinforced beam for flexural strength

4.7.2 Nylon BCR

Figure 4.41 compare the flexural strength of concrete beams reinforced with Nylon braided rebars against those that are unreinforced. The data shows that beams reinforced with Nylon fourth layer have a flexural strength of 4.60 MPa, which is an increase of 42.71% over the unreinforced beam's strength of 3.22 MPa. Similarly, beams with Nylon fifth layer reinforcement exhibit a strength of 4.76 MPa, marking an increase of 47.73% compared to the unreinforced beam.

These results highlight the beneficial impact of BRC on the flexural strength of concrete beams, suggesting that such reinforcement can significantly enhance the structural integrity and load-bearing capacity of concrete structures. The percentage increases in flexural strength for Nylon fourth and Nylon fifth layers demonstrate the potential for BRC to contribute to more durable and resilient construction materials as per IS standards.

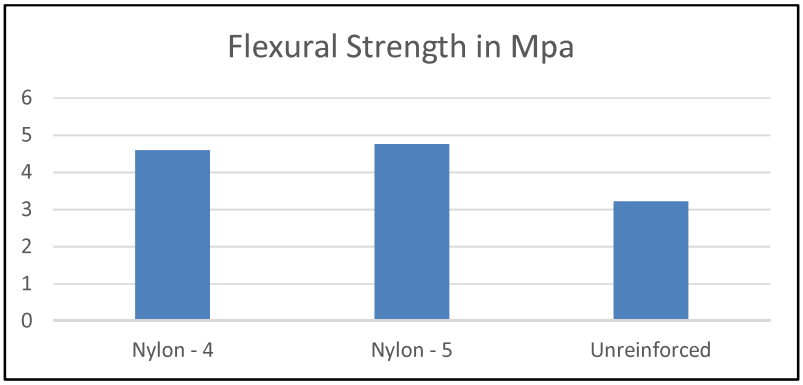


Figure 4.41 Comparison of BCR with unreinforced beam for flexural strength

4.7.3 Basalt BCR

Figure 4.42, presents a comparison of the flexural strength of concrete beams reinforced with Basalt braided rebars against those that are unreinforced.

The data indicates that beams reinforced with Basalt fourth layers have a flexural strength of 7.61 MPa, which is an increase of 136.25% over the unreinforced beam's strength of 3.22 MPa. Similarly, beams with Basalt fifth layer reinforcement exhibit a strength of 9.29 MPa, marking an increase of 187.97% compared to the unreinforced beam. These findings underscore the significant enhancement in flexural strength provided by Basalt braided rebars, suggesting that such reinforcement can greatly improve the structural integrity and load-bearing capabilities of concrete structures. The substantial increases in flexural strength for Basalt fourth and Basalt fifth layers underscore the potential of BCR to contribute to the development of more robust and enduring construction materials.

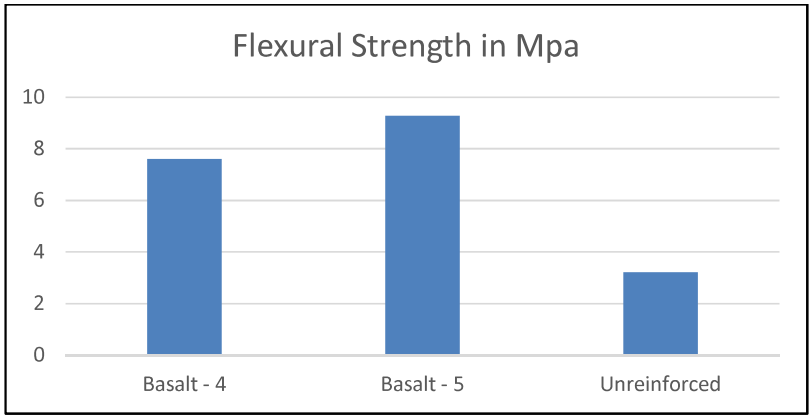


Figure 4.42 Comparison of BCR with unreinforced beam for flexural strength

4.7.4 PP + Basalt BCR

Figure 4.43 compare the flexural strength of concrete beams reinforced with PP + Basalt braided rebars against those that are unreinforced. The data shows that beams reinforced with PP + Basalt fourth layers have a flexural strength of 6.97 MPa, which is an increase of 116.25% over the unreinforced beam's strength of 3.22 MPa. Similarly, beams with PP + Basalt fifth layer reinforcement exhibit strength of 8.23 MPa, marking an increase of 155.37% compared to the unreinforced beam. These results highlight the significant improvement in flexural strength achieved through the use of PP + Basalt braided rebars, indicating that this composite material can substantially enhance the structural performance and durability of concrete beams. The marked increases in flexural strength for both PP + Basalt fourth and PP + Basalt fifth

layers demonstrate the effectiveness of BCR in reinforcing concrete structures, offering a promising solution for construction that requires higher strength and longevity.

This data illustrates that the integration of PP and basalt FRP bars markedly enhances the flexural strength of concrete beams. Increasing the number of layers from four to five further boosts this strength, indicating a positive correlation between the number of reinforcement layers and flexural strength. The stark contrast with the unreinforced beams underscores the effectiveness of using PP and basalt FRP bars in improving the structural performance and load-bearing capacity of concrete beams.

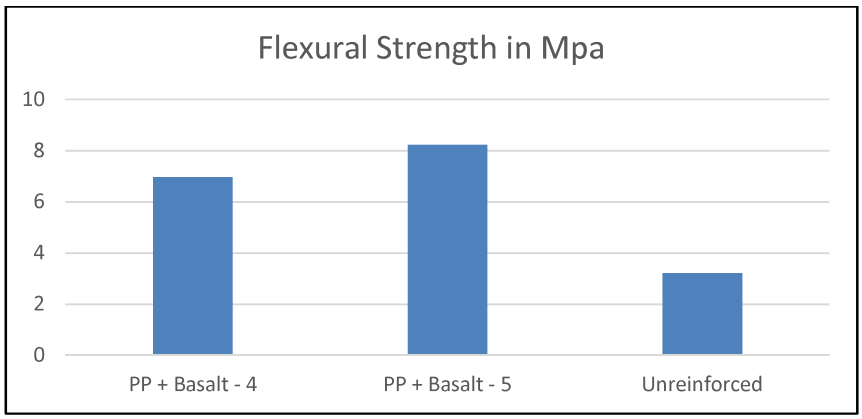


Figure 4.43 Comparison of BCRwith unreinforced beam for flexural strength

4.7.5 Nylon + Basalt BCR

Figure 4.44 present a comparison of the flexural strength between concrete beams reinforced with Nylon + Basalt braided rebars and those that are unreinforced. The data indicates that beams reinforced with Nylon + Basalt fourth layers have a flexural strength of 6.41 MPa, which is an increase of 98.70% over the unreinforced beam's strength of 3.226 MPa. Similarly, beams with Nylon + Basalt fifth layer reinforcement exhibit strength of 7.479 MPa, marking an increase of 131.86% compared to the unreinforced beam. These results underscore the substantial enhancement in flexural strength provided by the Nylon + Basalt braided rebars. The significant improvements in flexural strength for both the 4 and 5 layers of reinforcement affirm the efficacy of Braided BCR in bolstering the structural integrity and durability of concrete beams, offering a robust alternative for construction projects that demand increased strength and extended service life.

This data clearly demonstrates that the hybrid reinforcement with nylon and basalt FRP bars

significantly boosts the flexural strength of concrete beams. The increase in the number of layers from four to five further enhances this strength. The comparison with the unreinforced beams highlights the substantial improvement in structural performance and load-bearing capacity achieved through the use of combined BCR reinforcement.

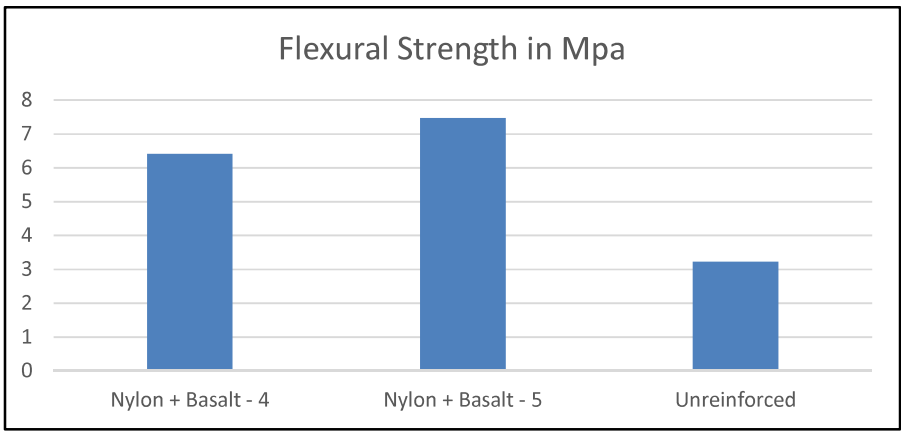


Figure4.44 Comparison of BCR with unreinforced beam for flexural strength

Chapter - 5
A MATHEMATICAL MODEL FOR PREDICTION OF TENSILE BEHAVIOR

This section introduces the significance of braided ropes in various industries, such as marine, construction, and sports, where strength and durability are crucial. The strength of these ropes is influenced by multiple factors, including the strength of individual yarns and the braiding pattern. Conducting extensive experiments to determine the strength of different configurations is resource-intensive, prompting the need for a mathematical model to predict rope strength based on key parameters. The study aims to develop a robust model using curve fitting techniques, addressing a gap in existing research on predicting the strength of braided ropes.

Mathematical Model

The strength of a braided rope is dependent on the strength of the individual yarns and the number of yarns braided together. To predict the strength of a braided rope with 'N' yarns, a mathematical model is proposed. This model allows for the input of parameters such as single yarn strength and the number of yarns, facilitating predictions without the need for extensive experimental data. The section emphasizes the use of curve fitting methods to establish a relationship between these variables.

Curve Fitting

Curve fitting is described as a method to find a mathematical relationship between two or more variables. This process involves plotting observations on a graph and drawing a smooth curve that approximates the data. The goal is to derive an equation that best fits the observed data, which can then be used for predictions. The section highlights the importance of curve fitting in establishing reliable models for predicting tensile strength in braided ropes.

Types of Curve Fitting Methods

This section outlines various curve fitting methods, including:

- Linear Regression: Suitable for linear relationships, assuming a direct correlation between independent and dependent variables.

- Polynomial Regression: Fits a polynomial function to capture nonlinear relationships, using higher-degree polynomials.
- Exponential Regression: Models growth or decay processes with an exponential function.
- Power Regression: Fits a power function, useful when one variable is a power of another.
- Logarithmic Regression: Models relationships where the dependent variable changes at a decreasing rate.
- Spline Interpolation: Divides data into segments, fitting a polynomial function to each segment for a smooth curve.

Principle of Least Squares

This section discusses the **least squares method**, a statistical technique used to find the best-fitting curve for a set of data points. The key points include:

- **Definition**: The least squares method aims to minimize the sum of the squares of the residuals (the differences between observed and predicted values). It helps in determining the curve that best fits the given data.
- **Data Representation**: The section defines the data as pairs of observations ((x*i, y*i)) for (i = 1, 2, \ldots, n). A curve (c: y = f(x)) is plotted based on these observations.
- **Error Calculation**: For each observation, the error (or residual) is calculated as the difference between the observed value (y*i) and the predicted value from the curve (f(x*i)). The total error is expressed as: $ S = \sum*{i=1}^{n} (y*i - f(x_i))^2 $ The goal is to find the curve that minimizes this sum.
- **Goodness of Fit**: The goodness of fit is assessed by evaluating how well the curve approximates the data. A lower value of the sum of squared errors indicates a better fit.
- **Application**: The principle of least squares is applied to both linear and nonlinear models, allowing for the fitting of various polynomial degrees to the data. The section emphasizes the importance of selecting the appropriate model to achieve accurate predictions.

Curve Optimization

This section focuses on the practical application of curve fitting to optimize the prediction of tensile strength in braided ropes. Key elements include:

- **Data Collection**: The section outlines the collection of experimental data regarding the maximum force (tensile strength) and the number of yarns used in the braided ropes.
- **Error Checking**: Various polynomial degrees (linear, quadratic, cubic, etc.) are tested to determine which provides the best fit for the data. The section includes Python code snippets demonstrating how to calculate and visualize the errors associated with different polynomial fits.
- **Results**: The results indicate that a **5th-degree polynomial** provides the best fit for the data, as it minimizes the error compared to lower-degree polynomials. The fitted equation is presented, along with the corresponding error metrics.
- **Visualization**: Graphs are generated to visually compare the observed and predicted values, illustrating the effectiveness of the fitted model. The section emphasizes the importance of visualizing data to understand the relationship between the number of yarns and tensile strength.

Investigation of Strength Prediction Models for Braided Ropes Made from Different Materials begins by examining the tensile strength of ropes constructed from nylon, polypropylene (PP), and basalt. The analysis highlights how the strength of these ropes varies with the number of yarns used. Experimental data shows that nylon ropes exhibit significant increases in strength as more yarns are added, which is modeled using polynomial regression to derive predictive equations. This curve fitting analysis not only illustrates the relationship between yarn count and strength but also sets the stage for understanding how different materials perform under similar conditions.

The section further explores **reverse curve fitting**, where the roles of independent and dependent variables are switched. This approach allows to analyze how variations in tensile strength (Y) impact the number of yarns (X). By applying the same curve fitting techniques with Y as the independent variable, the study provides insights into the number of yarns required to achieve specific tensile strengths, enhancing the understanding of material behavior.

A **comparative analysis** follows, contrasting the performance of nylon, basalt, and polypropylene ropes. Key findings indicate that nylon consistently demonstrates the highest tensile strength, while basalt, although strong, is less effective when mixed with nylon. Polypropylene ropes show variability in strength, suggesting that their performance can fluctuate based on the number of yarns. This analysis underscores the importance of selecting the right material based on specific application requirements, such as desired strength and flexibility.

The section concludes by emphasizing the **importance of curve fitting** in material analysis. Curve fitting serves as a valuable tool for understanding relationships between variables and predicting outcomes in material science. It helps identify outliers, optimize model parameters, and enhance interpretability, which are crucial for practical applications in engineering.

Challenges in Curve Fitting outlines the various challenges associated with this modeling technique. It highlights the sensitivity of curve fitting to outliers, where even a single anomalous data point can skew results and lead to inaccurate predictions. Many curve fitting methods assume a linear relationship between variables, which may not always hold true, particularly in complex datasets. The risks of overfitting—where a model is too complex and closely follows the data points, including noise—and underfitting—where a model is too simplistic to capture the underlying trend—are discussed.

Choosing the right model parameters, such as the degree of polynomial, is critical for achieving accurate results. The section also addresses interpretability issues, noting that while some curves may fit the data well, they may lack clear interpretability, especially in nonlinear cases. Additionally, the assumption of equal variance among residuals can lead to biased estimates if violated, and multicollinearity among multiple independent variables can complicate the interpretation of results.

Advanced Fiber-Reinforced Composites explores the mathematical modeling of composite rods made from blends of nylon, basalt, and polypropylene. This section emphasizes the need for accurate modeling to predict the mechanical properties of these hybrid materials. The analysis includes curve fitting techniques applied to assess the tensile strength of composite rods, allowing for predictions based on varying compositions and yarn counts.

The section discusses how different material combinations affect the overall strength of the composites, providing insights into their performance in various industrial applications. The findings suggest that the choice of materials and their proportions significantly influence the mechanical properties of the composites, guiding their application in different fields.

CHAPTER 6
CONCLUSION

The work entitled Optimization of Braided Structure for Civil Engineering Applications is an attempt to make composite rebars with the help of braiding technology. The composite rebars available contain parallel-laid glass fibres bound together with fiber ridges as reinforcement material. This ridges help in binding the fiber as well as increasing the bond strength with concrete. The diameter of these composite bars is much greater than the steel rebars. To overcome the disadvantage of these rebars and to have better tensile and flexural strength, better bonding with concrete without fibre ridges and all this with lesser diameter, braided composite rods were developed.

These braided composite rods have better inter-yarn bonding due to the intertwining process, at the same time separate fibre ridges have not to be bound as a naturally rough surface is obtained in this process. The prepared BCRs were made using different yarns like Polypropylene, Nylon, and Basalt and their combinations. This was done to study the effect of the type of material on the properties of composite rods. Also rods with different diameters were prepared to understand the effect of diameter on the properties of BCRs. The increase in the diameter was accomplished by the braid over braid technique.The choice of material and the number of layers significantly impact the performance characteristics of braided ropes.

The tensile test results for Polypropylene (PP) braided ropes and rods reveal a consistent increase in their ability to handle greater force as the number of layers increases. This is reflected in the rising rope g/lm (grams per linear meter) values, with the first layer withstanding a force of 513.30 Kgf and the fifth layer handling 1051.51 Kgf. The displacement values remain stable across all layers, indicating that the material maintains a stable elongation under stress. The fiber volume fraction across different layers of PP material shows that fibers constitute approximately 41% of the material in the initial layer, with this fraction changing as the number of layers increases. This allows for customization of the composite material's properties, making it suitable for a wide range of applications. The rod strength of PP braided composite rods increases with the diameter, from an ultimate load capacity of 786.12 Kgf for the initial layer with a 5.00 mm rod diameter to a maximum strength of 1889.88 Kgf for the fifth layer with a 7.84 mm rod diameter. However, as the diameter increases, the load-bearing

capacity of the PP braided composite rod decreases, attributed to the outer layers bearing more load compared to the inner layers.

Nylon braided ropes and rods exhibit enhanced performance characteristics with each additional layer. The ropes show a significant improvement in load-bearing capacity, as evidenced by the progressive increase in rope g/lm values across layers. The first layer withstood a maximum force of 657.82 Kgf, while the fifth layer handled 1392.05 Kgf. Despite the increase in layers and slight fluctuations, the maximum displacement remains relatively constant, indicating stable elongation under stress. This makes nylon ropes suitable for heavy loads due to their improved force handling capabilities and for heavy-duty applications where strength and minimal stretching are essential. On the other hand, nylon rods demonstrate a substantial increase in ultimate load (2845.35 Kgf) and stress (422.86 MPa), suggesting an effective balance between strength and flexibility. Although the modulus of elasticity is slightly lower at 16.63 GPa, this is due to the increased load-bearing capacity.

The tensile test results for basalt braided ropes and rods reveal a progressive increase in maximum force and rope g/lm values across layers. The first layer withstood a maximum force of 508.32 Kgf with a displacement of 5.38 mm, while the fifth layer handled 1073.11 Kgf with a displacement of 4.67 mm. Despite the increase in layers, the maximum displacement remains relatively constant, suggesting that basalt braided ropes maintain stable elongation under stress. This makes them an excellent choice for applications requiring high tensile strength and stability. The rod strength of basalt braided composite rods increases with the diameter. The initial layer features a rod diameter of 5.00 mm and an ultimate load capacity of 786.12 Kgf. This increases to a maximum strength of 2209.05 Kgf for the fifth layer with an 8.54 mm rod diameter. As the diameter increases, the load-bearing capacity of the basalt braided composite rod decreases. This can be attributed to the fact that with a larger diameter, the outer layers bear more load compared to the inner layers.

The tensile test results for PP + Basalt braided ropes and rods demonstrate an increase in maximum force and rope g/lm values with each additional layer. The first layer withstood a maximum force of 652.74 Kgf with a displacement of 28.12 mm, while the fifth layer handled 1324.52 Kgf with a displacement of 26.47 mm. This indicates that combining PP with basalt enhances the load-bearing capacity while maintaining stable elongation under stress.As the number of layers increases, the rope's ability to handle greater force also increases, as reflected

in the rising rope g/lm values. The fiber volume fraction across different layers of PP + Basalt material indicates that fibers constitute approximately 35% of the material in the initial layer, with this fraction changing as the number of layers increases. The rod strength of PP + Basalt braided composite rods increases with the diameter. The initial layer features a rod diameter of 5.00 mm and an ultimate load capacity of 621.27 Kgf. This increases to a maximum strength of 847.19 Kgf for the fifth layer with a 7.84 mm rod diameter. As the diameter increases, the load-bearing capacity of the PP + Basalt braided composite rod decreases, which can be attributed to the fact that with a larger diameter, the outer layers bear more load compared to the inner layers.

The tensile test results for Nylon + Basalt composite materials in both braided ropes and rods demonstrate superior characteristics. The braided ropes show significant enhancement in tensile properties, with the first layer withstanding a maximum force of 768.33 Kgf and a displacement of 20.34 mm, while the fifth layer handles 1473.11 Kgf with a displacement of 18.22 mm. As the number of layers increases, the rope's ability to handle greater force also increases, reflected in the rising rope g/lm values. The composite rods, with a Nylon to Basalt ratio of 50:50, display the highest ultimate load (2869.29 Kgf) and stress (468.34 MPa) among the composites, with a strain percentage of 18.96%. The modulus of elasticity is 26.76 GPa, indicating exceptional strength and moderate stiffness due to the synergistic effect of Nylon and Basalt. As the diameter increases, the load-bearing capacity of the Nylon + Basalt braided composite rod decreases, attributed to the fact that with a larger diameter, the outer layers bear more load compared to the inner layers. The fiber volume fraction across different layers of Nylon + Basalt material indicates that fibers constitute approximately 49% of the material in the initial layer, with this fraction changing as the number of layers increases.

A comparison between Nylon braided rebars and traditional steel rebars in terms of their performance in a concrete block pullout test, which evaluates bond strength, shows that the ultimate load capacity of the Nylon rebars is lower than that of the steel rebar. However, the ultimate stress for Nylon rebars is comparable to that of the steel rebar. For example, the fourth layer Nylon rebar handles 227.06 kN and the fifth layer handles 328.73 kN, compared to the steel rebar's 357.16 kN. The ultimate stress for the fourth layer is at 99.68 MPa and the fifth layer at 143.68 MPa.

The data indicates that reinforced beams exhibit significantly higher flexural strength. For instance, the Polypropylene - 4 layer shows a strength of 5.48 MPa and the Polypropylene - 5 layer shows 5.79 MPa. In contrast, the unreinforced beam has a flexural strength of only 3.22 MPa. This translates to an increase in flexural strength of approximately 69.91% for the Polypropylene - 4 layer and 79.27% for the Polypropylene - 5 layer compared to the unreinforced beam. These results underscore the effectiveness of Braided FRP Re-bars in enhancing the flexural strength of concrete beams, which could lead to more resilient structures capable of withstanding greater stress and load as per IS standards.

The proposed mathematical model offers a cost-effective and efficient alternative to traditional experimental testing methods, accurately predicting rope strength by considering key parameters such as yarn strength and braiding configuration. Further refinement of the model could enhance its accuracy and applicability in real-world scenarios, contributing to advancements in material science and engineering. Additionally, the analysis of the relationship between yarns and tensile strength in braided ropes, alongside investigations into composite rods, underscores the significance of accurate mathematical modelling in optimizing composite material properties. Leveraging curve fitting techniques and machine learning, these studies provide practical guidance for enhancing the design and performance of braided ropes and composite materials across various applications, fostering continued advancements in the field.

Together summarising all above braided composite reinforcement bars, it could be suitable for applications where rods are expected to sustain heavy loads without significant stretching. The high tensile strength and stable elongation under stress make it a good choice for applications that require durability and resilience. For instance, they could be used in the construction industry for reinforcing concrete structures, where the rods would need to bear significant loads. The ability of these high performance materials to maintain a stable elongation under stress would also be beneficial in applications that involve constant or repetitive movement, such as in the manufacturing of heavy-duty industrial equipment or automotive parts. The varying fiber volume fraction across layers allows for customization of the composite material's properties, making it suitable for a wide range of applications.

However, an increase in layer count and diameter doesn’t always lead to better performance, emphasizing the need for optimization in design. Similarly, the choice of material greatly

affects the performance of braided ropes. Insights from tensile tests and weight characteristics across different layers aid in material selection for various applications. In essence, both material selection and engineering design are pivotal in optimizing the bond strength of FRP bars used in concrete structures, thereby ensuring their durability. The composition and layering of materials significantly influence the rods' flexural and pull-out strength. Notably, braided composite rods, especially those combining PP and Basalt, show potential as an alternative to traditional steel rebars, providing a balanced mix of strength, elasticity, and stiffness. Hence, braided FRP rebars, particularly those integrating different materials, present a promising avenue for improving the durability and structural integrity of concrete structures in civil engineering.

Future Scope of Work

The field of braiding and braided composites holds significant potential for innovation and application across various industries. Here are key areas for future exploration:

1) **Diverse Braiding Techniques**: Expanding beyond traditional braiding methods, such as the maypole technique, can lead to new structural properties and mechanical advantages. By exploring various braiding techniques, researchers can discover optimal methods tailored to specific applications, fostering creativity and innovation in product design.
2) **Specialized Geometries**: Investigating non-standard braided shapes, like hexagonal or triangular configurations, can meet unique industrial needs that conventional shapes may not address. These specialized designs can enhance load distribution and structural integrity, making them suitable for demanding applications while also allowing for aesthetic innovations in decorative products.
3) **Integration with Smart Technologies**: Incorporating sensors and smart materials into braided composites can revolutionize their functionality. Smart technologies can enable real-time monitoring of structural integrity, enhancing safety and performance across various fields, including construction and automotive.
4) **Sustainability in Materials**: Exploring eco-friendly fibers and sustainable production practices is essential in today's environmentally conscious market. Researching renewable materials can lead to sustainable products that meet consumer demand for greener alternatives, helping to reduce the industry's carbon footprint.

The future of braiding and braided composites is rich with opportunities for innovation. By focusing on diverse techniques, specialized geometries, high-performance fibers, and sustainability, the industry can drive advancements that meet the evolving needs of various sectors.

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PUBLICATIONS

❖ *CONFERENCE PUBLICATION:*

1. Oral presentation at Texcon 2020 themed on a contemporary issue in textile manufacturing process from fiber to garment, Title:-"Analysis of braided composite, along with Dr. AadharMandot, held on 5th and 6th March 2020 at SVVV- Indore.

2. Oral presentation at Texcon 2024 themed on Fashion, Product Design and Technology-Challenges and Opportunities" Title :- Study The Effect Of Layers And Braid Angle For Mechanical Properties Of Braided Composite Rods, along with Dr. AadharMandot, held on 1st and 2nd March, 2024.

❖ *PAPER PUBLICATION:*

Title:- "Study the Effect of Layers and Braid Angle on Mechanical Properties of Biaxial Braided Composite Rods",

Journal of the Textile Association,

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❖ *PATENT PUBLICATION:*

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