CHAPTER – 1
INTRODUCTION AND RESEARCH OBJECTIVES

1.1 Background and origin of the topic

Concrete ranks as the second most utilized material worldwide, following water. It has witnessed a rapid increase in global usage from 6.7 billion tons in 2000 to 17.5 billion tons in 2017[1]. The construction sector, consuming 40% of all materials and energy production, faces sustainability challenges. Cement and steel, concrete's primary constituents, contribute significantly to carbon emissions and energy consumption[2]. Researchers aim to develop replacements to enhance long-term sustainability. Incorporating supplementary cementitious materials (SCMs) such asground granulated blast furnace slag (GGBFS) and fly ash into concrete can notably reduce greenhouse gas emissions[3]. Portal et al. [4] reported that steel reinforcement exhibits the highest energy demands, followed by carbon, AR (alkali-resistant) glass, with basalt reinforcement having the lowest energy requirements. Textile Reinforced Concrete (TRC) shows promise as a substitute for steel-mesh-reinforced facades, offering durability and environmental benefits.

Textile-reinforced concrete (TRC) merges the compressive strength of concrete with the tensile strength, flexibility, and durability of textile materials. This composite material comprises a cementitious matrix and embedded textile fabrics.

According to A.E. Naaman [5] '*Textile reinforced concrete is a type of reinforced concrete commonly constructed of hydraulic-cement matrix reinforced with several layers of closely spaced continuous 2D textiles, or one or several layers of 3D textiles. At least one textile layer should be placed near each of the two extreme surfaces of the resulting structure. The textiles may be made of polymer, synthetic, metallic, organic or other suitable materials. The fineness of the cementitious matrix and its composition should be compatible with the textile armature system it is meant to encapsulate. The matrix may contain discontinuous fibres or microfibres of appropriate dimensions.*'

Textiles can be incorporated into concrete in three forms: discrete fibres, continuous fabric, and a combination of both. Discrete textiles, encompassing natural fibres (jute, hemp, flax, coir, sisal, bamboo, kenaf, banana, and pineapple), man-made fibres (polypropylene, polyester, nylon, and polyethylene), and high-performance fibres (carbon, glass, basalt, aramid, polyvinyl alcohol, polybenzoxazole, and steel), have proven effective as reinforcements in fibre-reinforced concrete (FRC) [6]–[9]. FRC enhances strain hardening, toughness, and crack resistance through fibre bridging, with optimal performance achieved at a limited fibre inclusion of 3% in the concrete mix [10], [11]. Despite various advantages, constraints exist due to potential voids and poor bonding with longer fibres. FRC cannot fully replace primary reinforcement in slender elements with a fibre volume fraction exceeding 5% [12]. Challenges in achieving smooth surfaces and controlling fibre orientation exist with discrete fibres, making the integration of yarns and textiles a more flexible and customized reinforcement option compared to fibrillated film.Continuous textile assemblies, including various yarn types, unidirectional and bidirectional fabrics, nonwovens, three-dimensional fabrics, braided structures, fabric composites, FRP laminates, and rods, play a crucial role in reinforcing and strengthening concrete. The specific fibre type, fineness, volume fraction, and orientation significantly impact the performance and load-bearing capacity of Textile-Reinforced Concrete (TRC) [13]. Utilizing continuous yarn and fabric reinforcement allows for optimizing parameters to meet specific reinforcement requirements. Achieving high-volume reinforcement content with desirable characteristics is possible through precise control of alignment and proportion in fabric structures, making it ideal for creating thin cementitious elements [14]. Fabric reinforcement enhances the tensile and flexural properties of cement composites, displaying strain-hardening behaviour and improved bonding due to the fabric's non-linear geometry [15]. Additionally, textile reinforcement enhances resistance to lateral forces during seismic loading and provides resistance to wind loads [16]. Spatial knitted fabric serves multiple purposes, including flexible formwork and reinforcement for complex prefabricated elements with directional material properties aligned with the applied load direction [17]. Commercially available non-metallic textiles, used for strengthening purposes such as carbon, glass, basalt, or polyphenylene bezobisoxazole(PBO) fibre textiles, generally exhibit mesh sizes ranging from 8 to 30 mm, with weights typically falling within the range of 150 to 600 g/m^2, contingent upon the specific fibre material [18].

Concrete boasts commendable resistance to compressive forces, and to counterbalance tensile forces, reinforcement is incorporated. However, conventional metallic reinforcements, such as steel rebars, are susceptible to corrosion, necessitating a thick concrete cover for protection. This becomes a challenge when attempting to create thin concrete elements with metallic reinforcement. In contrast, alternative materials such as high-performance textiles (basalt, carbon, aramid, glass, etc.) exhibit corrosion resistance and demand minimal cover, offering a promising solution to this challenge[19]. Additionally, escalating demand for the repair and upkeep of current building structures comes with a substantial cost. Consequently, researchers are actively seeking durable and sustainable construction alternatives. One notable solution involves substituting conventional steel-based metallic reinforcements with non-metallic high-performance textile reinforcements. Integrating textile reinforcement into concrete enables the creation of slender, lightweight, and durable structures. This incorporation not only enhances design flexibility but also allows for the production of structural components with intricate shapes and predetermined properties[20]. Furthermore, the use of textile reinforcement presents the possibility of cost savings by minimizing material consumption. These innovative reinforcements offer numerous benefits, including being lightweight, non-corrosive, possessing high tensile strength, flexural strength, ductility, toughness, exhibiting pseudo-ductile behaviour with large deformations due to multiple cracking, moldability, and displaying resistance to alkaline substances.Structures reinforced with textile materials have demonstrated enhanced resistance to flexure, impact, fatigue, and seismic events [21]. TRC structures exhibit superior durability, extended longevity, and diminished maintenance and repair costs over time. TRC is employed for reinforcing beams, columns, walls, and slabs, as well as for constructing thin-shell structures and precast elements [11].

Textile structures, when used as a reinforcement component in concrete, provide a distinctive capability to tailor structures according to external load requirements. This customization encompasses variations in fibre/filament type, yarn linear density, the number of yarns per unit length (warp and weft), yarn fineness in warp and weft directions, yarn orientation (unidirectional, bidirectional, multidirectional), through-thickness reinforcement (3-D or spacer fabric), and the utilization of hybrid yarn and fabric[22], [23].

The geometric profile of yarn within the cementitious matrix plays a crucial role in determining its tensile properties and bonding effectiveness. Yarns with crimped profiles, featuring additional curvature, demonstrate outstanding frictional bonding with the cementitious matrix, leading to a high pull-out load. Yarn crimping occurs during fabric formation and is influenced by factors such as weave design, yarn fineness, and warp and weft density. Fabrics with coarse yarns and higher interlacement points generally exhibit increased crimp formation. However, it's important to note that crimped yarns may introduce stress concentration in the matrix, potentially limiting the full reinforcement capability of the composite[12].

Monofilament yarn demonstrates superior reinforcing efficiency when compared to multifilament yarn, indicating restricted matrix penetration in multifilament bundles. High-Density Polyethylene (HDPE) stands out with the highest flexural strength and reinforcing efficiency, attributed to its elevated elastic modulus [24]. Polyethylene (PE) yarn with a crimped geometry demonstrates higher flexural strength compared to straight geometry, suggesting enhanced filament-matrix bonding and strain-hardening behaviour. Additionally, PE yarn with crimped geometry displays ductile behaviour under tensile loading. The bond strength is directly correlated with the yarn's elastic modulus, with higher modulus yarns such as Kevlar® and High-Density Polyethylene (HDPE) exhibiting stronger bonding attributed to clamping stress from autogenous shrinkage. Conversely, low modulus yarns like PE, PP, and Nylon exhibit inferior bond strength due to the Poisson’s effect [25].

A study investigated the influence of different roving fineness (320, 640, 1200, and 2400 tex) on alkali-resistant (AR) multifilament glass roving when used to reinforce concrete [26]. An increase in yarn tex number resulted in a decrease in peak pull-out stress, attributed to poor matrix penetration, higher void presence, and reduced filament-matrix contact. The peak pull-out stress reduced from 1015 to 335 Nmm^{-2} as tex increased from 320 to 2400, leading to a decline in reinforcing efficacy from 0.94 to 0.34. Nevertheless, pull-out force, interfacial stiffness, and fracture toughness increased with a larger roving cross-section. Coarse roving specimens exhibited a gradual deviation from linearity and a stress decrease after the peak stress, while finer roving specimens experienced a sudden drop due to filament rupture. The increase in filament diameter had a more significant impact on the roving's mechanical performance than increasing the number of filaments. Utilizing two 640 texrovings instead of one 2400 tex roving resulted in a 50% material saving and a 25% higher pull-out load, making it suitable for lightweight and high-performance Textile-Reinforced Concrete (TRC) applications.

In another study, the pull-out and flexural behaviour of polyethylene monofilament yarn reinforced cementitious composites were investigated [12]. Two yarn configurations were tested: straight yarn and crimped yarn (detached from woven fabric). The crimped yarn exhibited a higher pull-out load than the straight yarn at all embedment lengths (10, 15, and 20 mm) due to mechanical anchoring from its geometry. At longer embedment lengths (20 mm), the fabric's pull-out load slightly improved compared to crimped yarn, but the crimped yarn's contribution remained dominant. In terms of flexural behaviour, crimp density did not influence the first crack stress, indicating that crimp geometry played a more significant role in enhancing post-cracking behaviour.

In a separate study, the external bond behaviour of a Nylon multifilament bundle was examined in four different configurations: straight, twisted, two twisted bundles combined by additional twisting (2x twisted), and 2x twisted bundle with latex coating [25]. Twisting was found to enhance bond strength as the rough surface facilitated mechanical anchorage and improved filament-matrix bonding. However, the application of latex coating, resulting in a smooth surface, and the use of a 2x twisted bundle did not contribute to an enhancement in filament-matrix bonding in cement composites.

The commingled yarn comprises AR glass and water-soluble polyvinyl alcohol (PVA) filaments in a 95:5 ratio [27]. Embedded in a cementitious matrix, PVA dissolution creates interstices, promoting matrix penetration and enhancing filament-matrix bonding. Despite having 30% lower tensile strength than AR glass roving, the commingled yarn outperforms in concrete pull-out load tests. Biaxial warp knitted fabrics from commingled yarn-based TRC components exhibit an 80% higher strength than those from parent AR glass filaments [28]. Comparing spread yarn, hybrid commingled yarn, and parent AR glass yarn, pull-out loads for spread yarn and commingled yarn are 300% and 80% higher, respectively, than the parent AR glass yarn bundle. TRC components from biaxial warp knitted fabrics with spread yarn and commingled yarn show tensile strengths 30% and 80% higher, respectively, than those from parent AR glass-based fabrics.

Jamshaid et al. [29] examined how Basalt, polypropylene, polyester, and jute yarns behave when reinforced in ordinary Portland cement (OPC) and geopolymer cement (GPC) matrices, and studied the effects of alkaline exposure on yarn durability. Basalt and jute demonstrated strong bonding with minimal slippage and crack opening, although jute had lower load values due to reduced strength. PET and PP yarns exhibited weaker bonding, leading to increased slippage and wider cracks, making them unsuitable for load-bearing concrete elements. The higher twist in PP yarn improved interfacial shear strength. Yarn failure mechanisms included pull-out, rupture, and telescopic failure. Alkaline treatment (pH 10-12) resulted in decreased mechanical properties for alkali-treated jute and PET yarns due to hydrolysis. Conversely, Basalt and PP yarns experienced minimal strength reduction, rendering them suitable for concrete reinforcement. Combining Basalt's strain-hardening ability with PP and PET's high ductility has the potential to enhance the properties of cement composites and improve yarn-matrix bonding.

The hybrid fabric structure, akin to hybrid yarn structure, blends different materials for synergistic performance. This involves either (a) using two or more fabric layers with different materials in concrete or (b) employing a single fabric with different yarns in varied orientations. Hybridization enables the amalgamation of low-cost, low-modulus yarns (e.g., PP, PE, PET) with high-cost, high-modulus yarns (e.g., carbon, aramid, basalt, AR glass) to achieve excellent mechanical properties cost-effectively. Carbon-polypropylene hybrid woven fabric in concrete beams displays flexural toughness 6.5-40.75 times higher than that of unreinforced concrete beams [30]. The choice of fabric influences the impact behaviour of Textile-Reinforced Concrete (TRC) slabs, with glass fabric exhibiting the least damage due to high energy absorption, followed by basalt fabric. Hybrid TRC exhibits more significant spalling and local failure. However, combining basalt and glass (hybrid fabric) demonstrates the highest impact resistance, absorbing more energy at lower levels (50 J). Hybrid textiles show the lowest mid-span deflection at higher energy levels (100 J and 200 J). A full factorial analysis indicates a significant interaction between fabric type and energy levels for all TRC types [31]. In a separate study, a weft-inserted warp knitted hybrid fabric was developed, combining ductile, cost-effective PP yarns with high-performance aramid yarns. The resulting fabric alternated equal amounts of PP and aramid yarns with 2 mm loops. The hybrid TRC composite demonstrated comparable tensile strength to aramid-only TRC, despite using half as many aramids' yarns. Surprisingly, the hybrid TRC composite exhibited superior tensile behaviour compared to PP-only TRC. However, the hybrid system's bond strength was lower than aramid-only TRC, likely due to reduce aramid yarn content. In summary, the hybrid TRC proves cost-effective and exhibits comparable tensile properties to aramid-only TRC [15].

The flexural behaviour of hybrid braided structure reinforced concrete specimens was compared with various reinforcements, including uncoated and epoxy-coated AR glass yarn, uncoated and epoxy-coated carbon yarn. The hybrid braided structure, composed of AR glass roving (core) and polypropylene yarn (sheath), demonstrated a significant 57.71% increase in flexural strength compared to unreinforced concrete. While epoxy-coated carbon and AR glass specimens exhibit superior flexural behaviour in TRC, their higher cost and labour-intensive processes should be considered. Notably, carbon reinforcement outperforms all other variants with a flexural strength of 40.8 MPa [32].

Hybrid braided structures, incorporating cores of Basalt, AR glass, and carbon rovings along with a polypropylene filament sheath, demonstrated varied flexural strengths [33]. Carbon-based structures exhibited the highest strength, followed by AR glass, while basalt structures showed the lowest. The hybrid structure outperformed the parent structure, surpassing unreinforced specimens in flexural behaviour. Reinforced samples displayed ductile behaviour, characterized by substantial deformations before failure, making them preferable for earthquake design. Beyond flexural strength, the use of hybrid structures increased energy absorption, particularly in basalt hybrid structures, showcasing enhanced strength and energy absorption at different depths.

1.2 Research Motivation

High performance fibres such as Carbon, AR glass, basalt have found large interest in composite industry. These fibres have superior mechanical properties and are non-corrosive in nature making them suitable for building infrastructure applications in form of fibre reinforced plastics (FRPs) and textile reinforced concrete (TRC).The hybrid yarn structure can help to combine the superior tensile properties of high-performance fibres and ductile behaviour of PP and PET's fibres and has the potential to enhance the properties of cement composites and improve yarn-matrix bonding. Previous research confirms the greater advantages of hybrid yarn and fabric structure in concrete in terms of cost and mechanical properties however limited research was done in this area[28]–[32], [34], [35]. The yarn structural modification such as twist, crimped geometry also has positive effect on the pull-out (fibre-concrete bond) behaviour of TRC.

High-performance yarn bundles, such as carbon, comprising thousands of fine filaments, are prone to abrasion and filament breakage during the weaving process. A solution to this challenge involves adopting a core-sheath structure, where a sheath made of polypropylene fibre is applied over the core of the high-performance filament bundle using the DREF-3 spinning process. The resulting core-sheath structure undergoes a short heat-setting process to preserve the integrity of the sheath fibres during weaving. This ensures that the sheath remains intact while maintaining adequate flexibility for the weaving process. This approach has proven effective in reducing filament breakage during weaving operations. Furthermore, the DREF spinning process ensures a very high rate of production with minimal or no damage to the core yarn. Importantly, this method enables the production of hybrid yarns with a diverse range of core-to-sheath ratios without introducing twist to the core bundle[36], [37].

Cable yarn is created by uniformly and spirally wrapping a surface filament strand (surface yarn) over a core filament strand (core yarn) without twisting the individual strands [38]. This principle is also applied in hollow spindle spinning, wrap spinning, and co-wrapping techniques. The core filament offers load-bearing strength, while the surface filament serves to protect the core from abrasion and provides a ribbed surface texture for mechanical anchorage in Textile-Reinforced Concrete (TRC) [20].

Taking into account the aforementioned aspects, the current research aimed to investigate the impact of the hybrid (core-sheath) yarn structure on the mechanical properties of Textile-Reinforced Concrete (TRC).

1.3 Research Objectives

The present study aims at developing a hybrid yarn structure that can be incorporated in woven fabric structure which have good mechanical interlocking (anchorage) effect with cementitious matrix (mortar). To fulfil this objective core-sheath hybrid yarns have been produced using DREF3 spinning method and helical wrapping was done using direct twisting and braiding machine to incorporate helical configuration of PET yarn in the core yarn strand. The hybrid yarn structure is woven into woven scrim fabric (mesh fabric) and coated with epoxy resin. The fabric is reinforced into concrete specimen to investigate pull-out, tensile and flexural properties.

The following are the sub-objectives for the present work:

(i) To developcore-sheath yarn structures using Basalt, Carbon and AR glassroving (as core components) and polypropylene fibre(as sheathfibres) using DREF-3 spinning method.

(ii) To incorporate helical configuration in yarn structure: (a) Twisting of PET filaments through Direct twisting machine,(b) helical wrapping of twisted PET filaments on core-sheath yarn structure through braiding machine.

(iii) To compare the tensile behaviour of parent and hybridyarn structuresand their corresponding plain-wovenfabrics.

(iv) To investigate the influence of parent and hybrid yarn structures on the yarn pull-out behaviour of fabric-reinforced concrete.

(v) To compare the pull-out behaviour of fabric-reinforced concrete and evaluate the effectiveness of yarn structure used for helical wrapping, formed through: (a) direct twisting, and (b) braiding machine.

(vi) To compare the tensile, and flexural characteristics of concrete reinforced with woven fabric made from hybrid yarn structures and parent yarn structures.

(vii) To examine the influence of combined reinforcements, comprising of discrete polypropylene fibres and a woven fabric structure (TRC), and compare them with plain (unreinforced) concrete, and polypropylene fibre-reinforced concrete (FRC), in terms of their mechanical properties.

1.4 Structure of the Thesis

Chapter 1: Introduction and Research Objectives

The first chapter offers abackground and introduction to the topic, outlines the motivation for the research, and delineates the research objectives.

Chapter 2: Literature Review

This chapter reviews existing literature on research conducted in the proposed area. It begins with a discussion on textile structures, textile-reinforced concrete (TRC) and its different fabrication methods for concrete reinforcement. The review also covers hybrid yarn manufacturing methods suitable for producing reinforcement for concrete applications and their advantages. Additionally, it examines yarn and fabric parameters affecting TRC properties, methods of improving fibre-concrete bonding, the importance of coating textiles, and the effect of combined reinforcements (fibre and fabric) on TRC behaviour.

Chapter 3: Materials and methods

In this chapter, the raw materials and their suppliers are initially mentioned, followed by the production of a core-sheath yarn structure using the DREF-3 spinning technique. The core comprises high-performance basalt, AR glass, and carbon, while the sheath consists of polypropylene fibres. Thermal heat setting is then employed to enhance the weavability and structural integrity of the hybrid yarn. Subsequently, cable yarn is developed using twisted

PET filaments through a braiding machine. This cable yarn is woven into a plain weave scrim fabric using a handloom, with flexible inserts maintaining the distance between subsequent picks, later removed after weaving. The scrim fabric facilitates the flow of cementitious mortar, and the grid size is selected considering the size of the fine aggregate. Following this, resin treatment, specifically epoxy resin coating, is applied to improve the fabric's structural stability and prevent distortion during handling. The resin treatment binds the multifilament in the core yarn strand, creating a monofilament-type effect and enhancing load-bearing ability. The process continues with the fabrication of Textile-Reinforced Concrete (TRC) elements (plate specimens) using the casting method in fabricated formworks. Tensile tests on yarn and fabric specimens are conducted, followed by pull-out tests, uniaxial tensile tests, and flexural tests on the TRC specimens.

Chapter 4: Results and Discussions

This chapter presents the results of tensile tests for yarn and fabric specimens through load-displacement graphs. It discusses the influence of hybrid yarn structures (core-sheath and cable yarn) on the tensile properties of yarn and fabric. The tensile behaviour of basalt, AR glass, and carbon-based hybrid yarn and fabric is compared, revealing improved tensile behaviour in both yarn and fabric tests for the hybrid yarn, with carbon offering the highest tensile behaviour.

The chapter also examines the yarn pull-out, uniaxial tensile, and flexural behaviour of fabric-reinforced concrete, focusing on the impact of yarn structural modifications such as hybrid yarn structures. Additionally, a comparative analysis of the pull-out, tensile, and flexural behaviour of basalt, AR glass, and carbon-based fabric-reinforced concrete is presented. The mechanical test results highlight an improvement in the pull-out, tensile, and flexural behaviour of FRCM specimens reinforced with hybrid yarn compared to control specimens, with carbon FRCM exhibiting the best performance in all tests compared to basalt and AR glass. Finally, the cracking details and failure patterns of FRCM specimens under tensile and flexural tests are analysed.

Chapter 5: Summary and Conclusions

This chapter provides a summary of the main findings and conclusions derived from the studies reported in the previous chapter.Suggestions for future work in the realm of yarn structural modification, hybrid yarn, and hybrid fabric-based Textile-Reinforced Concrete (TRC).Finally, the references and literatures used for this study are listed.