

T.R.
EGE UNIVERSITY
Graduate School of Applied and Natural Science

**DEVELOPMENT OF INNOVATIVE HIGH
PERFORMANCE TEXTILE PRODUCTS AND
TEXTILE REINFORCED CEMENT BASED
COMPOSITES FOR REINFORCEMENT IN
DAMAGED BUILDINGS**

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Textile Engineering Department Textile Engineering

Second Cycle Programme

İzmir

2024

Elifsu Hazal MORGÜL tarafından yüksek lisans tezi olarak sunulan “Development Of Innovative High Performance Textile Products and Textile Reinforced Cement Based Composites for Reinforcement in Damaged Buildings-Hasarlı Binalarda Güçlendirme Amaçlı Yenilikçi Yüksek Performanslı Tekstil Ürünlerinin ve Tekstil Donatılı Çimento Esaslı Kompozitlerin Geliştirilmesi” başlıklı bu çalışma EÜ Lisansüstü Eğitim ve Öğretim Yönetmeliği ile EÜ Fen Bilimleri Enstitüsü Eğitim ve Öğretim Yönergesi’nin ilgili hükümleri uyarınca tarafımızdan değerlendirilerek savunmaya değer bulunmuş ve 04.09.2024 tarihinde yapılan tez savunma sınavında aday oybirliği/oyçokluğu ile başarılı bulunmuştur.

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ABSTRACT

Development Of Innovative High Performance Textile Products And Textile Reinforced Cement Based Composites For Reinforcement In Damaged Buildings

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July 2024, 87 pages

This study investigates the development of high-performance textile products and textile-reinforced cement-based composites for building reinforcement. Three types of Dyneema® fiber yarns Dyneema®, twisted Dyneema®, and cored Friction spun yarn were evaluated for their production processes and mechanical properties. Various weaving procedures were employed to produce reinforcement fabrics, including warp sizing and density determination, with a focus on plain weave constructions due to their stability and suitability for reinforcement applications. Mechanical testing revealed that twisted Dyneema® yarn exhibited the highest strength, followed by Dyneema® and Friction spun yarns. Fabric properties including thickness, weight, bending resistance, air permeability, and strength were evaluated to assess their performance in reinforcement applications. Dyneema® yarn emerged as the most promising for commercial use due to its strength and production efficiency.

In conclusion, this study provides insights into advancing textile engineering and construction materials through innovative approaches and problem-solving.

Key words: textile reinforced concrete, Dyneema® fiber, woven fabric, plain weave, twill

ÖZET

Hasarlı Binalarda Güçlendirme Amaçlı Yenilikçi Yüksek Performanslı Tekstil Ürünlerinin Ve Tekstil Donatılı Çimento Esaslı Kompozitlerin Geliştirilmesi

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2024, 87 sayfa

Bu çalışma, bina takviyesi için yüksek performanslı tekstil ürünlerinin ve tekstil takviyeli çimento bazlı kompozitlerin geliştirilmesini araştırmaktadır. Üç tip Dyneema® elyaf ipliği bükümsüz Dyneema®, bükümlü Dyneema® ve Dref iplik, üretim süreçleri ve mekanik özellikleri açısından değerlendirildi. Stabiliteleri ve donatı uygulamalarına uygunluğu nedeniyle düz örgü yapılar odaklanarak, çözgü boyutlandırma ve yoğunluk belirleme dahil donatı kumaşları üretmek için çeşitli dokuma prosedürleri uygulanmıştır. Mekanik testler, bükülmüş Dyneema® ipliğinin en yüksek mukavemeti sergilediğini, bunu Dyneema® ve Dref ipliklerinin izlediğini ortaya koydu. Takviye uygulamalarındaki performanslarını değerlendirmek için kalınlık, ağırlık, eğilme direnci, hava geçirgenliği ve mukavemet gibi kumaş özellikleri değerlendirildi. Dyneema® iplik, gücü ve üretim verimliliği nedeniyle ticari kullanım için en umut verici iplik olarak ortaya çıkmıştır. Sonuç olarak, bu çalışma, yenilikçi yaklaşımlar ve problem çözme yoluyla tekstil mühendisliği ve inşaat malzemelerinin geliştirilmesine ilişkin içgörüler sunmaktadır.

Anahtar kelimeler: tekstil takviyeli beton, Dyneema® iplik, friksiyon spun yarn, dokuma kumaş, bezayağı, dimi

FOREWORD

This study investigates the development of innovative high-performance textile products and textile-reinforced cement-based composites to strengthen structures in earthquake-prone regions of our country. While single-layer fabrics made from carbon fibers are preferred due to their high load-bearing capacity and low density, they suffer from disadvantages such as high cost, brittleness, and recycling challenges. In this research, layered woven fabric structures with different yarn geometries based on high elastic modulus polyethylene fibers are developed as alternatives to carbon fiber polymers.

Additionally, the use of hybrid friction spun yarns aims to produce innovative, recyclable, and cost-effective textile products. The study introduces new approaches to enhance structural durability through various reinforcement applications and mechanical tests.

İZMİR

Elifsu Hazal MORGÜL

04/09/2024

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ACRONYMS

<u>Symbol</u>	<u>Definition</u>
TÜBİTAK	Scientific And Technical Research Council Of Turkey
TRC	Textile Reinforcement Concrete
FRC	Fiber Reinforcement Concrete
RC	Reinforcement Concrete
SRC	Steel Reinforcement Concrete
GFRG	Glass Fiber Reinforced Concrete
PE	Polyethylene
PES	Polyester
PVA	Polyvinyl alcohol
N	Newton
Sig.	Significance (p-value)
GSM	Grams per square metre

1. INTRODUCTION

Textile Reinforced Concrete (TRC) represents a significant advancement in the field of construction and civil engineering, combining the durability of concrete with the flexibility and strength of textile materials. Traditional concrete, while renowned for its compressive strength, often requires reinforcement to improve its tensile strength and resilience. Historically, steel rebar has been utilized for this purpose, but it has limitations such as susceptibility to corrosion, significant weight, and restrictions on design flexibility.

The development of TRC addresses these limitations by incorporating textile materials such as glass fibers, carbon fibers, and aramid fibers into the concrete matrix. These textile reinforcements offer several key benefits, including enhanced tensile strength, resistance to corrosion, reduced weight, and the ability to create more complex shapes and thin-walled structures. This makes TRC an attractive alternative for a wide range of applications, from architectural elements to structural components and infrastructure projects.

The use of textile-based reinforcement allows for more innovative and sustainable construction techniques. It opens up new possibilities for architectural design, enabling the creation of lightweight, aesthetically pleasing, and structurally sound elements that would be challenging or impossible to achieve with traditional reinforced concrete.

The objective of this thesis is to develop innovative high-performance textile products and textile-reinforced cement-based composites for structural reinforcement. For this purpose, single and multilayer fabrics were produced from high molecular weight polyethylene fibers with a high modulus of elasticity, as an alternative to carbon fiber. In addition to high-performance polyethylene fibers, hybrid Friction spun yarns produced from hemp fibers, a natural fiber with high strength, were utilized in fabric production. These efforts aim to create innovative, recyclable, cost-effective, and high-performance textile products that can serve as alternatives to existing solutions.

This study is also part of a TUBİTAK 1001 project, conducted in collaboration with the Civil Engineering Department of Ege University. To better present the results from the fabric production process and explain the selection of specific yarn types and fabric structures, data from their study was also included.



2. LITERATURE REVIEW

2.1 Historical Development Of Fiber Reinforced Concrete

For more than 4500 years, fibers have been used to strengthen matrices. In early civilizations, straw fibers were used to prevent cracking in sun-dried adobe bricks. However, in the following periods, engineers faced two major challenges: the low tensile strength and brittleness of concrete. The solution to these difficulties emerged in 1847 when a French engineer named Joseph Lambot introduced the idea of integrating continuous fibers, such as wire or wire mesh, into concrete. This innovation laid the foundation for the modern concept of reinforced concrete. The problem of insufficient tensile strength in concrete was addressed by the addition of continuous steel reinforcing rods to areas exposed to tensile forces (Naaman, A.E., 1985).

Throughout the 20th century, the use of steel rebar became the standard for reinforcing concrete in construction projects worldwide. Steel reinforcement significantly improved the structural capacity of concrete, allowing for the construction of larger and more complex structures. However, this method had its limitations, including susceptibility to corrosion and limited flexibility in complex shapes (Barman et al., 2024).

At the beginning of the 1950s, research on glass fibers was carried out in Russia, England, and the USA. These glass fibers were even employed in construction projects in Russia, but they were found to be susceptible to alkali attacks.

Since the early 1960s, fiber-reinforced concrete (FRC) has attracted increasing attention. The development of FRC reached a turning point during this time, with a variety of different fibers being introduced as more novel applications were discovered (Naaman, A.E., 1985).

The main advantage of using textiles in concrete reinforcement is the ability to create lightweight, corrosion-resistant, and flexible structures. Textile fibers can be used as short fibers (fiber-reinforced concrete) or woven into various fabric structures (textile-reinforced concrete), allowing for greater adaptability to complex shapes and

designs. Textile materials enhance the tensile strength and ductility of the concrete. When designing new buildings, the ability to cast thin elements increases design freedom. The low weight of textile-reinforced concrete elements offers numerous benefits, such as a lower dead load for the structure and simplified transportation. Additionally, textiles provide enhanced tensile strength without the risk of corrosion, a common issue with traditional steel reinforcement (Barman et al., 2024). Commonly used materials for fibers are:

- Steel Fibers
- Glass Fibers
- Natural Fibers
- Carbon Fibers
- Polypropylene Fibers

For effective reinforcement, the chosen material must exhibit exceptional bonding properties, high tensile strength, and favorable thermal compatibility. This ensures the seamless transmission of loads from the concrete to the interface between concrete and reinforcement, thereby upholding structural integrity. Therefore, reinforcing materials are selected to achieve a harmonious strain distribution throughout the concrete-reinforcement system (Behbahani et al., 2011).

2.2 Types Of The Textile Materials Reinforced Concretes

2.2.1 Fiber reinforced concrete

Fiber reinforced concrete consists of concrete or mortar mixed with randomly distributed short fibers. Combining short fibers with textile reinforced concrete generates an increased strength and a better crack pattern, with several small cracks instead of one or two larger cracks. The fibers can be made of many different materials for example steel or glass. This type of reinforced concrete is more of a homogenous material than for example steel reinforced concrete, although it still consists of two

different materials with different properties. Because of that, fiber reinforced concrete can be called a homogenous composite material (Holmberg, 2016).

The fibers can be of varying length, short fibers help bridging the smallest cracks and longer fibers help bridging larger cracks, see Figure 2.1.

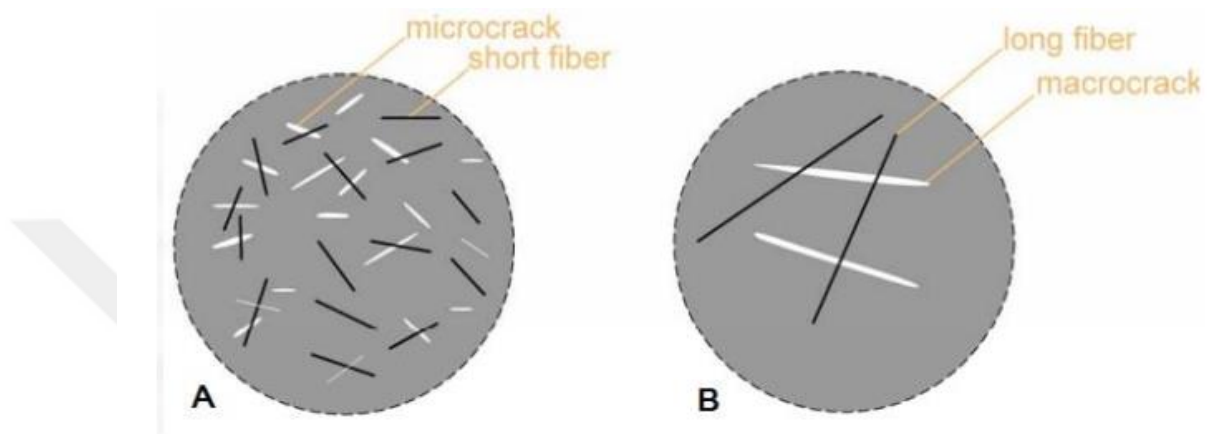


Figure 2. 1: Fibers bridging cracks (Holmberg, 2016).

2.2.2 Textile reinforced concrete

Cementitious materials, widely used in construction, are characterized by fragility and low tensile strength, making them susceptible to cracking. Enhancing their robustness and tensile capabilities is achievable through textile reinforcement, allowing for the creation of slender structures capable of withstanding significant deformation. This approach, known as textile-reinforced concrete (TRC), involves integrating textiles woven from metallic, non-metallic, or plant-based fibers to reinforce cementitious material (Rawat et al., 2022).

TRC constitutes a composite material merging technical textiles like carbon fibers with a concrete matrix. In recent years, it has emerged as a novel and valuable construction material, exhibiting advantages, including notable corrosion resistance, high ductility, and impressive strength (Peled et al., 2017).

TRC differentiates itself with the targeted positioning of textile reinforcement, providing optimum performance in stress-loaded areas. Its advantages over fiber-reinforced concrete (FRC) stem from its ability to exploit towing behavior through strategic reinforcement placement. Over the past decade, numerous studies have examined the strength, durability, coupling, behavior, modeling, and design methods of TRC. Considered a promising composite material, TRC offers high tensile load-carrying capacity similar to steel-reinforced concrete, promising advancements in the construction industry. Researchers note the significant potential of TRC to improve the mechanical properties of cement matrices (Alrshoudi, 2015). Figure 2.2 below shows the comparison between RC, FRC and TRC reinforcement systems.

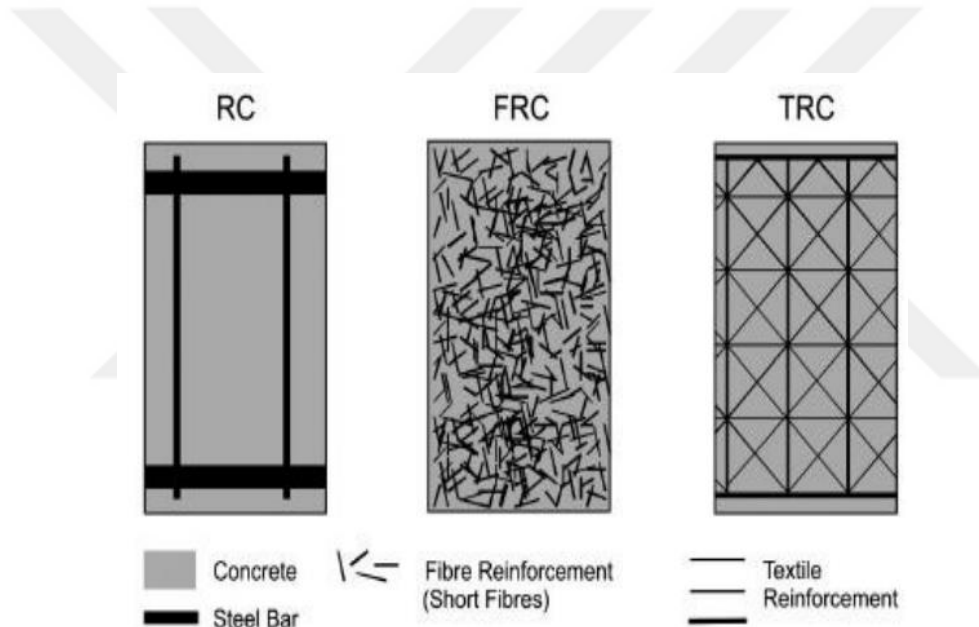


Figure 2. 2: Comparison between RC, FRC and TRC (Alrshoudi, 2015).

Unlike FRC, TRC enjoys a distinct advantage in its precise placement where stresses manifest. TRC blends aspects of traditional steel-reinforced concrete and chopped fiber-reinforced concrete optimally (Papanicolaou and Papantoniou, 2010). This strategic positioning optimally employs TRC's properties, unlike conventional fibers that are randomly distributed, yielding less efficient outcomes. Random fiber dispersion in FRC often results in underutilized properties for crack control, strengthening, and stiffening. Additionally, the presence of fibers has a limited impact

on the compressive zone strength of beams. In contrast, TRC effectively combines attributes of chopped fiber RC and conventional steel-reinforced concrete. Moreover, TRC's lower volume fraction compared to short fiber RC contributes to cost-effectiveness and improved efficiency (Alrshoudi, 2015). Table 2.1 concrete.

Table 2. 1: The key differences between the FRC and TRC.

Aspect	Fiber Reinforced Concrete (FRC)	Textile Reinforced Concrete (TRC)
Types of Fibers	FRC uses discrete, short fibers mixed directly into the concrete mix. These fibers can be made from various materials such as steel, glass, carbon, polypropylene, or nylon.	TRC uses continuous textile materials, typically in the form of woven or knitted fabric, meshes, or grids, embedded within the concrete. These textiles are often made from high-strength fibers like carbon, glass, or aramid.
Form and Distribution	The fibers in FRC are generally randomly dispersed throughout the concrete mix, offering isotropic reinforcement (uniform distribution).	TRC's textiles are placed strategically in layers within the concrete, providing directional reinforcement. This enables more control over the distribution of strength and flexibility.
Reinforcement Objective	FRC aims to improve specific properties such as tensile strength, crack resistance, impact resistance, and durability.	TRC is designed for enhanced structural integrity, flexibility, and the ability to create thinner and more complex shapes with greater strength-to-weight ratios.
Typical Applications	FRC is commonly used in applications where improved crack resistance, impact resistance, or toughness is desired, such as in pavements, slabs, precast products, and shotcrete.	TRC is typically used in architectural elements, thin-walled structures, complex shapes, and applications requiring lightweight yet durable construction. It is also used in applications requiring high resistance to corrosion or other environmental factors.
Manufacturing Process	FRC fibers are mixed into the concrete before or during placement, providing a simpler and more straightforward reinforcement method.	TRC involves placing textiles into concrete during casting, which may require more complex manufacturing processes and specialized techniques.

2.2.3 Fibers used in textile reinforced material

Fibers can be classified into two main groups based on their elastic modulus: those with a modulus higher than that of the concrete mix and those with a lower modulus. Vegetable fibers and polypropylene are classified as having a low elastic modulus, whereas fibers such as glass, carbon, and steel have a higher elastic modulus than the cement mortar matrix. Fibers with a high elastic modulus increase bending and impact resistance, while those with a low elastic modulus can enhance the impact resistance of concrete but have little effect on its bending strength.

Fibers are categorized into three groups based on their origin: metallic fibers (such as steel, carbon steel, and stainless steel), organic fibers, and mineral fibers (such as asbestos and glass fibers). Organic fibers are further divided into natural and synthetic subcategories. Natural fibers include plant-based fibers (such as sisal) and animal fibers (such as silk or animal hair fibers). Synthetic fibers are divided into artificial fibers, which can be either Manmade (such as nylon and polypropylene) or natural polymers (such as cellulose and protein fibers). The classification of fibers is illustrated in Figure 2.3 (Behbahani et al., 2011).

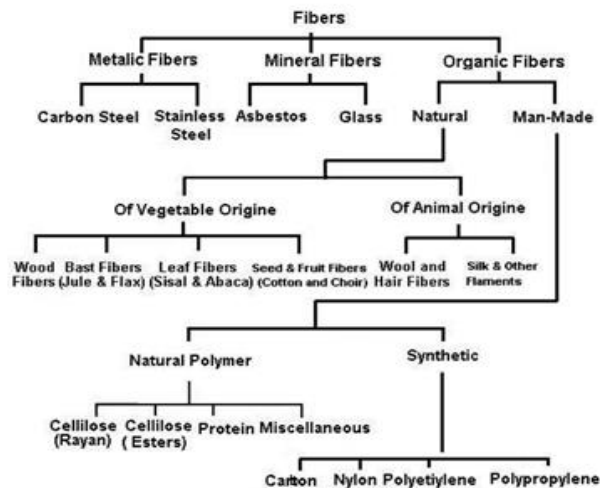


Figure 2. 3: Fibers classification (Behbahani et al., 2011).

2.2.3.1 Steel fiber

Steel fibers significantly enhance the compressive strength of concrete; therefore, they are added to the cement mix to improve both compressive and flexural strengths. The workability of concrete decreases as the volume ratio of steel fibers rises, but shear strength remains unaffected. Superplasticizers should be used in Fiber Reinforced Concrete (FRC) to address this issue (Behbahani et al., 2011).

By introducing Steel Fiber Reinforced Concrete (SFRC) to traditional Reinforced Concrete (RC) elements, the matrix's tensile strength increases, consequently boosting flexural strength and ductility. Steel fibers contribute various advantageous properties to concrete, including increased resistance to cracking, improved stiffness, ductility, enhanced impact resistance, wear resistance, and greater energy absorption (Behbahani et al., 2011).

Over the past three decades, SFRC (Steel Fiber-Reinforced Concrete) applications have significantly grown. SFRC, with its low cost, easy fabrication, and enhanced performance, is extensively used in civil engineering and large-scale construction projects (Zheng et al., 2018). SFRC is particularly valuable in high-performance concrete structures such as bridges, tunnels, and tall buildings. Additionally, it can replace traditional reinforcement in various structural applications (Kazhimkanuly and Chernavin, 2023).

2.2.3.2 Natural fibers

Natural fibers are appealing reinforcements in concrete due to their lightweight nature, cost-effectiveness, superior specific strength and modulus, and the absence of associated health risks. Their widespread availability makes them a practical choice for reinforcement in concrete structures (Anas et al., 2022).

The utilization of these fibers to enhance the strength and durability of brittle materials is not a novel concept. In cement concrete production, wood fibers have been

explored as viable reinforcement materials, offering the advantage of a higher elastic modulus and increased strength compared to other vegetable-based fibers (Shadheer et al., 2021).

Natural fibers have various applications in textile-reinforced concrete (TRC), with jute, basalt, and cellulose fibers frequently employed as reinforcement materials (Shadheer et al., 2021). Most natural fibers are suitable for use in the construction of roads and sustainable dwellings. Natural fiber-reinforced TRC is a versatile solution with a range of applications in construction and structural engineering fields (Scholzen, et al., 2015). Jute is a prime example of using agricultural waste to produce natural fibers, aligning with circular economy concepts and waste utilization strategies (Bheel et al., 2021).

In conclusion, natural fiber-reinforced TRC has diverse applications, including waste reduction, aesthetic improvements, structural strengthening, lightweight construction, sustainable practices, retrofitting, and restoring old structures. By incorporating natural fibers in TRC, an environmentally friendly alternative is introduced, fostering avenues for advanced and sustainable building methodologies (Jamshaid et al., 2022).

2.2.3.3 Manmade fibers

In TRC, manmade fibers play a vital role and have various uses. They are employed in creating high-performance fibers for 3D printing, concrete reinforcement, sports equipment, military and transportation applications, and textiles (Coppola et al., 2017)

Manmade fibers in TRC possess qualities contributing to concrete strength and performance:

- **Tensile Strength:** Alkali-resistant glass, carbon, basalt, and polymer fibers offer high tensile strength, effectively withstanding tensile stresses (Yoo et al., 2016).

- **Adhesion:** The smooth surfaces of Manmade fibers promote improved adhesion to the concrete matrix, enhancing load-transfer capacity.

- **Water Resistance:** Unlike natural fibers, Manmade fibers resist water absorption, ensuring the durability of TRC.

- **Processing:** Manmade fibers' even distribution within the concrete matrix is facilitated by their ease of integration.

- **Corrosion Resistance:** Manmade fibers resist corrosion, ensuring the long-term durability of TRC (Azevedo et al., 2021).

- **Cost-Effectiveness:** Compared to natural fibers, manmade fibers like polypropylene and polyethylene are often more cost-effective (Azevedo et al., 2021).

- **Durability:** Manmade fibers exhibit resistance to degradation over time, showcasing good long-term durability. The prolonged performance of TRC is facilitated by their resilience to external variables, including temperature variations and chemical exposure (Deng et al., 2021).

- **Flexibility:** Manmade fibers offer design and application flexibility. Their versatility in TRC reinforcement includes various forms such as chopped fibers, continuous multifilaments, and pre-made textiles.

In summary, manmade fibers in TRC provide advantageous attributes, including robust tensile strength, adhesion, water resistance, ease of processing, corrosion resistance, cost-effectiveness, durability, and flexibility. These qualities collectively contribute to the overall strength and longevity of TRC structures (Rylko et al., 2022).

Enhanced mechanical properties, crack resistance, lightweight design, and corrosion resistance are among the numerous benefits of incorporating Manmade

fibers into TRC (Le et al., 2021). The elastic modulus, tensile strength, aspect ratio, distribution, content, and orientation of the fibers all significantly impact the mechanical characteristics of Manmade fiber-reinforced concrete (Zhao et al., 2021).

The use of manmade fibers in TRC spans various applications, yielding advantageous outcomes.

Manmade fibers such as basalt, carbon, alkali-resistant glass and polymer fibers are essential for structural improvement in TRC. While increasing the load-bearing capacity and tensile strength of concrete buildings, manmade fibers with a uniform surface texture increase adhesion and preserve the consistency and workability of concrete by preventing water permeability. (Asgharzadeh and Raupach, 2018).

In conclusion, the utilization of manmade fibers in TRC offers diverse benefits, contributing to structural improvement and enhancing concrete properties (Azevedo et al., 2021).

2.2.3.4 Glass fibers

For over four decades, the construction industry has benefited significantly from Glass Fiber Reinforced Concrete (GFRC). Glass fibers enhance tensile strength, reducing the need for steel reinforcement and mitigating steel reinforcement corrosion in structures exposed to hydraulic and maritime environments. GFRC, with its distinct composition, exhibits more intricate characteristics compared to conventional concrete.

Numerous parameters can affect the characteristics and functionality of GFRC, such as the ratio of cement to water, porosity, composite density, filler and fiber content, fiber length and orientation, curing techniques, and manufacturing accuracy (Anas et al., 2022). GFRC excels in impact strength and energy absorption without significantly compromising compressive strength. The type of glass fibers used, such as E-glass and alkali-resistant (AR) glass fibers, and environmental factors are crucial for enhancing long-term performance (Iskender and Karasu, 2018).

In the construction industry, GFRC is frequently employed for non-structural components such as façade panels, pipelines, and channels. GFRC is lightweight, fire-resistant, attractive, and strong (Bishetti, 2019).

Architectural panels made of GFRC can lower transportation and repair costs due to their lightweight nature. It is crucial to consider the type of glass fibers used and environmental factors to enhance the long-term performance of GFRC (Tabalvandani et al., 2011).

2.2.3.5 Carbon fibers

Carbon fiber is frequently used in textile-reinforced concrete (TRC) due to its exceptional mechanical qualities, such as high elastic modulus and tensile strength. TRC is a composite material consisting of corrosion-resistant textile reinforcement and high-strength, fine-grained concrete (Asgharzadeh and Raupach 2019). In specific scenarios, such as the construction of double walls, using carbon fiber-reinforced concrete instead of steel-reinforced concrete can reduce embodied carbon emissions by up to 25% (Friese et al., 2022). This demonstrates how the use of carbon fiber in TRC can have favorable environmental benefits.

Carbon fibers find diverse applications in TRC, offering numerous advantages:

- **Building Surface Repair and Reinforcement:** TRC, reinforced with carbon fibers, is used in construction for surface repair and reinforcement, enhancing load-bearing capacity.
- **Retrofit Applications:** Carbon fiber-reinforced TRC is employed to improve the structural performance of existing concrete structures (Mattarollo et al., 2023).

- Construction of Thin-Walled, High-Performance Components: Carbon fiber-reinforced TRC enables the construction of lightweight yet strong components (Bielak et al., 2020).

- Applications for Composite Materials: Carbon fiber-reinforced textiles are frequently used in composite materials to enhance strength in industries such as automotive, marine, and aerospace.

In conclusion, carbon fiber is crucial to TRC due to its benefits, including high tensile strength, lightweight design, and sensing capabilities. Applications include improving composite material performance and minimizing embodied carbon emissions, in addition to repairing and retrofitting building surfaces. Ongoing research aims to discover new advancements and enhance the use of carbon fiber in TRC for various construction purposes (Kaushik et al., 2022).

2.2.3.6 Basalt fibers

Basalt, a volcanic rock, is utilized in reinforced applications due to its excellent physical, chemical, and thermal properties. Basalt fibers, produced from melted and extruded basalt rock, exhibit high strength, good corrosion resistance, and high thermal stability. These characteristics make basalt fibers suitable for use in reinforcing concrete and other building materials, enhancing their durability and performance (Cherif, 2016).

In construction, basalt fibers are used to produce textiles and composites that reinforce concrete structures. These basalt-reinforced composites improve the mechanical properties of concrete, such as tensile and compressive strength, and provide enhanced resistance to cracking and environmental degradation. Basalt fibers are also favored for their resistance to alkaline environments, making them suitable for applications in harsh conditions (Peled et al., 2017).

The use of basalt fibers in reinforced applications helps create more robust and long-lasting infrastructure, contributing to the development of innovative building materials and techniques in modern construction (Peled et al., 2017).

2.2.3.7 Polyethylene fibres

Renowned for their high tensile strength, PE fibers play a pivotal role in enhancing the overall strength and load-bearing capacity of the concrete matrix. This inherent strength contributes to heightened tensile strength and load-bearing capabilities, fortifying the concrete matrix (Reis, 2009).

PE fibers exhibit uniform and smooth surfaces, promoting robust adherence to the concrete matrix and efficient load transfer (Anandamurthy et al., 2017). Notably, these fibers maintain TRC's durability and structural integrity by resisting water absorption (Reis, 2009). Their straightforward integration into concrete mixtures and homogeneous distribution throughout the matrix streamline TRC production. Their flexibility in design and application lends versatility to TRC reinforcement (Ozdemir and Bilisik, 2021).

These fibers offer advantages such as vapor permeability, fire resistance, and substrate compatibility, making them useful for external reinforcement in various structures (Dalalbashi et al., 2018). These fibers play an important role in repairing and strengthening building surfaces, creating durable textile materials, and strengthening concrete and epoxy composites (Zhang et al., 2022). Additionally, PE fibers improve the bending abilities of TRC beams, outperforming their steel fiber reinforced concrete counterparts (Yoo et al., 2016).

They also contribute to mitigating cracking in TRC, enhancing material performance and integrity. The versatility and advantageous properties of PE fibers make them integral to the advancement of TRC technology, offering solutions for reinforcement, durability, and enhanced structural performance (Neves and Felicíssimo, 2020).

2.3 Fabric Structures Used In Textile Reinforced Concrete

In textile reinforced composites, the reinforcement takes the form of a textile fabric, usually consisting of a network of Manmade or natural fibers. The size, shape, length, orientation, architecture, and material of the fibers can be adjusted to design a fiber-reinforced composite with specific properties. Engineering composites find wider applications when more complex reinforcement designs such as woven, knitted, or braided textiles are used. In woven fabrics, warp and weft threads typically form two perpendicular strands that are interwoven to form a self-supporting textile structure. Warp and weft strands are woven together to form multilayer woven fabrics, sometimes called 3D weaves. Yarns are intertwined in highly organized loop connections to create knitted fabrics. Depending on the direction of the loops, weft weaves and warp weaves are two main categories. Braided fabrics contain three or more strips woven in an overlapping criss-cross pattern. Biaxial and triaxial weaves are the two most common types. Another option is 3D knitted fabrics, characterized by their multi-layered structure.

Each textile manufacturing technique offers unique advantages and disadvantages, which should be carefully considered based on the specific requirements of the application (Zhalmuratova et al., 2020). In the Table 2.2 below, the summary of textile production methods and their advantages and disadvantages are explained in detail.

Table 2. 2: Summary of Textile Production Methods for Fabricating Tissue Constructs and Their Advantages and Disadvantages (Zhalmuratova et al., 2020).

Production Method	Advantages	Disadvantages
Knitting	High flexibility	Adjusting properties in different directions is difficult
Weaving	Ability to create 3D complex structures using CAD systems Ability to create constructs with anisotropic properties	Less flexibility compared to knitting Low porosity

	Process is less mechanically harsh compared to knitting	
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Woven reinforcements and knitted reinforcements represent the two main categories for textile reinforcements. Woven reinforcements integrate threads in a regular pattern, enhancing the strength and stability of the composite material. Their structural integrity and design flexibility make woven fabrics common in high-performance applications. In contrast, knitted reinforcements involve binding loops of yarn together, resulting in a more resilient and flexible structure. Knitted reinforcements are preferred when fit and flexibility are paramount.

Woven reinforcements offer several advantages. They excel in load-bearing applications due to their high strength and rigidity. Woven fabrics can shape complex forms and curved surfaces, owing to their drape and conformability. Moreover, woven reinforcements offer a plethora of design options, including various weave patterns and fiber orientations that can be tailored to meet specific performance criteria (Huang et al., 2015).

2.3.1 Woven Fabrics

Weaving, a practice with roots dating back millennia, has undergone a transformation from manual to mechanical and, most recently, to automated methods, enabling the production of intricate fabrics (Figure 2.4). This ancient technology, depicted in the figure, has led to a fascinating convergence of high-tech and mass-produced commodities. Modern weaving, an area of technology utilizing highly advanced machinery, generates everyday, low-tech products.

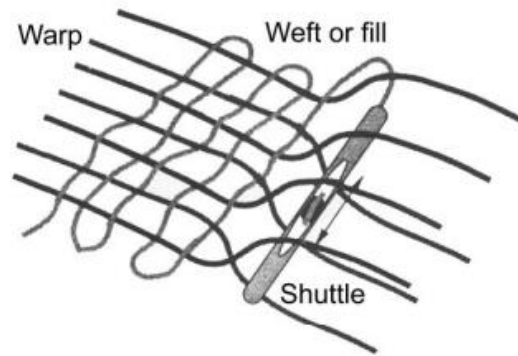


Figure 2. 4: Weaving (Verpoest and Jones, 2017).

Nevertheless, woven materials have played a historical role in load-bearing applications, such as the sails of ships, where incredibly durable textiles were developed centuries ago. In recent decades, 'technical textiles,' especially those tailored for composites, have gained prominence. These textiles serve a distinct purpose, meeting specialized requirements primarily as reinforcement, unlike traditional textiles.

Fabrics are sought after for structural applications due to their enhanced impact resistance, ease of handling, and low fabrication cost. Woven fabrics constitute a significant portion of textiles used in composite applications. However, they come with drawbacks, including low in-plane shear resistance, diminished yarn-to-fabric tensile properties, limited conformability, and reduced translation efficiency due to yarn crimp (Verpoest and Jones, 2017).

2.3.1.1 Woven Fabric Structure

Standard 2D woven fabrics consist of at least two yarn systems crossing one another at a straight angle. Warp yarns run in the direction of production, while weft yarns run transversely. The weave pattern, determining the fabric's look and characteristics, has a considerable impact. Figure 2.5 shows the fabric construction of woven types (Cherif, 2016).

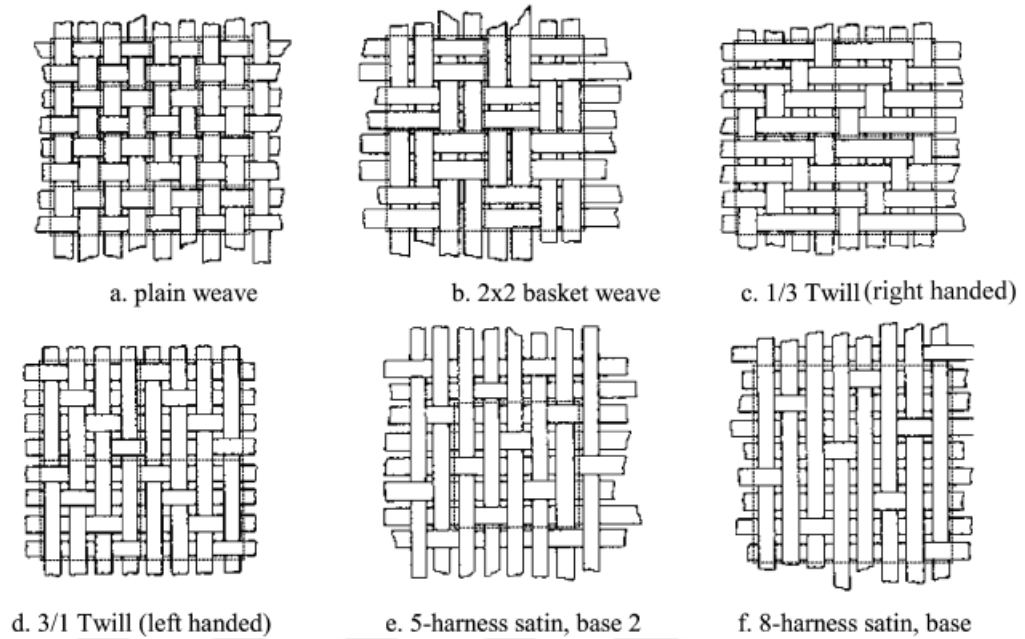


Figure 2. 5: Fabric construction forms and their fabric repeat (Cherif, 2016).

Schematic representation

The weave pattern of woven cloth is typically depicted as simple colored fields in a grid of squares rather than graphical renditions of appearance (Figure2.6).

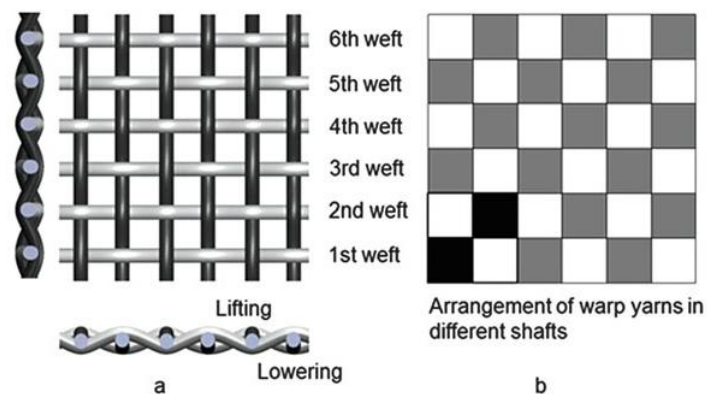


Figure 2. 6: Schematic representation of a woven fabric with (a) a cross-section in warp and weft direction and (b) weave diagram (Cherif, 2016).

2.3.2 Basic weave patterns

Three basic weave patterns, satin, twill, and plain weaves, are commonly utilized in woven fabrics. Each pattern has a repeating unit with an equal number of warp and weft threads.

2.3.2.1 Plain Weave

Plain weave is the simplest form of interlacing and the most common basic weave pattern (Figure 2.7). It has a repeat unit of two warp and two weft yarns. The first warp yarn is raised over the first weft and then lowered under the second weft whereas the second warp yarn is lowered under the first weft and raised over the second weft. The plain weave is the most closely interlaced weave pattern with the highest crimp. This results in a high shear resistance and good handling characteristics, but also causes a loss of strength and stiffness. The high crimp of plain weaves causes a significant difference between fiber orientation and angle of maximum stress and significantly reduces the load-carrying capacity (Cherif, 2016).

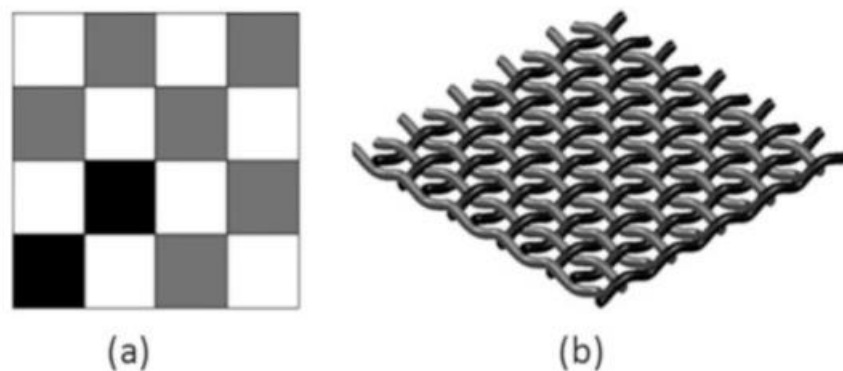


Figure 2. 7: (a) Plain weave diagram with 4 repeat units, (b) schematic diagram (Cherif, 2016).

2.3.2.2 Twill weave

Twill weave is defined by a minimal repeat unit of three warp and three weft threads, resulting in distinct diagonal lines. The basic type, weft-faced twill, involves raising one warp yarn over one weft yarn and lowering it beneath two other weft yarns, forming a diagonal line from the bottom left to the top right of the fabric. Both weft-faced and warp-faced twills have fabric backs that look quite similar (Cherif, 2016).

2.3.2.3 Satin weave

Satin weave, named for its smooth surface and delicate interlacing, is the third basic weave pattern. Satin weaves allow higher warp and weft densities than plain and twill weaves. (see Figure 2.8) Five warp and five weft threads make up the smallest repetition unit in satin weaves. In this weave, one warp yarn is dropped beneath four weft strands and raised above one weft yarn. Satin weaves can be categorized as weft-faced or warp-faced, with differences in crimp and shear resistance (Cherif, 2016).

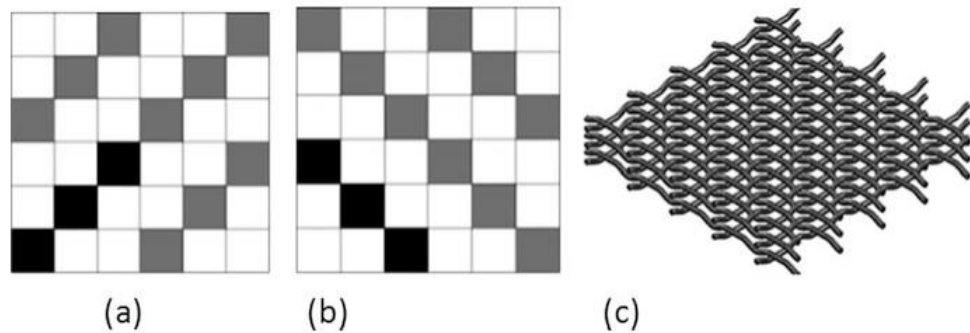


Figure 2. 8: (a) Weft faced twill with diagonal line going up, (b) weft faced twill with diagonal line going down (4 repeat units), and (c) schematic diagram (Cherif, 2016).

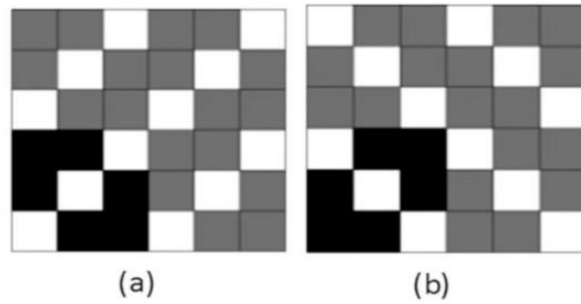


Figure 2.9: (a) Warp faced twill with diagonal line going up and (b) warp faced with diagonal line going down (4 repeat units) (Cherif, 2016).

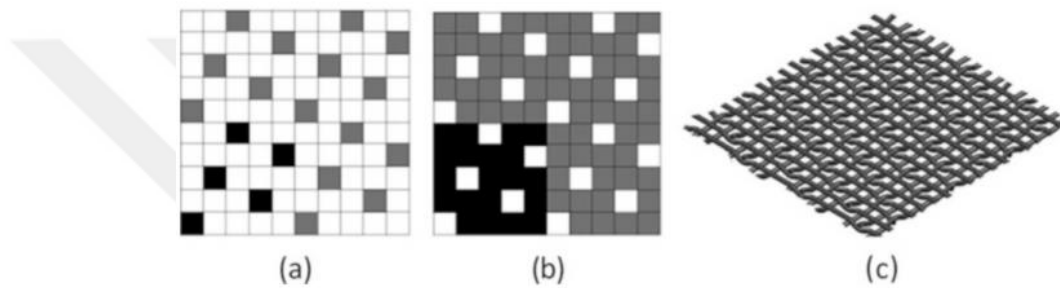


Figure 2.10: (a) Weft faced satin, (b) warp faced satin (4 repeat units), and (c) schematic diagram (Cherif, 2016).

2.3.2 Woven Fabric Parameters and Properties

2.3.2.1 Crimp

Crimp describes the deviation of a woven fabric's yarn from a straight orientation. The relationship between the length of a typical strip and the length of the yarn used to weave it is indicated by crimp. A balanced relationship between the crimp of warp and weft threads generally exists (Cherif, 2016).

2.3.2.2 Woven fabric density

Weft and warp yarn densities are typically expressed in yarns per centimeter. Increased yarn density contributes to enhanced slippage resistance of the woven cloth (Cherif, 2016).

2.3.2.3 Characteristics of the stress-strain behavior

The structural deformation and yarn deformation are two different zones that can be seen in the stress-strain behavior of woven fabrics. Structural deformation, occurring initially, involves significant elongation with relatively little force. Yarns align with the stress direction, rendering their material characteristics insignificant during this phase. The extent of elongation varies based on the weave pattern, with satin-woven fabrics exhibiting approximately 1% structural elongation, while plain-woven fabrics made of glass fibers show structural elongation ranging from 2-3%. Yarn deformation follows structural deformation, ceasing as the yarns stretch and their material qualities come into play (Cherif, 2016).

2.3.2.4 Bending Stiffness

Bending stiffness is a crucial factor in determining a fabric's drapeability and suitability for 3D geometries. Influenced by fiber type, architecture (weave pattern, yarn density), and filament adhesion, bending stiffness is affected by bending angle, length, and force. The cantilever method (horizontal orientation) and the patent-protected method (vertical orientation) are widely used test techniques. Utilizing bend-proof yarns and denser woven textiles increases bending stiffness, requiring higher force during draping, impacting component quality, reproducibility, and manufacturing procedures. These pressures relax the fabric, making it challenging to permanently model complex shapes (Cherif, 2016).

2.3.2.5 Permeability

Permeability serves as a gauge for liquids' ease of penetration into fabrics, crucial for infusion and barrier operations. A general rule states that higher permeability allows easier impregnation during composite development, resulting in lower density (Cherif, 2016).

2.3.2.6 Woven fabric thickness

The distance between the top and bottom edges of a fabric defines its thickness. The structure of the woven fabric and the type of fiber significantly influence thickness. Utilizing special woven fabrics like pile fabrics can decrease density while increasing the thickness of woven structures.structures (Cherif, 2016).

2.4 Knitted Fabric

Weft knitting is a technique for fabric creation where yarn is fed transversely on the needles, and stitches are produced to form the textile fabric. Stitches are joined to create the fabric, and the process involves the successive execution of the same work cycle on the needles throughout the working breadth. Differentiation between weft, cotton-type, and warp knitting lies in the direction of yarn feeding and the process step of stitch formation.(Figure 2.11) In warp knitting, stitch forming and yarn guidance occur simultaneously on all needles throughout the working width (Cherif, 2016).

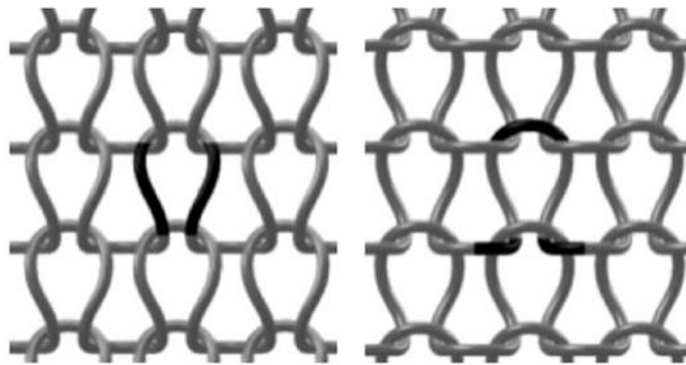


Figure 2. 11: Right and left stitch side of a right-left knitted fabric (Cherif, 2016).

2.4.1 Knitted fabric properties

Yarn type and knitting process parameters significantly influence the structure and properties of knitted fabric. Higher machine gauges result in increased stitch densities. Consistent yarn tension on all needles during yarn feeding is crucial for

achieving identical stitch length across the knitted fabric. Knitted fabrics exhibit three distinct behaviors: curling, stress-strain, and shear. The choice of machine and material enables the production of knitted fabrics with various properties, including drapability, specific mechanical qualities, or energy absorption capacities (Cherif, 2016).

2.4.2 Knitted reinforced concrete

The utilization of knitted materials as reinforcement in concrete applications is expanding. Weft-knitted textiles offer benefits such as improved flexural performance, better bond conditions, and the ability to produce complex geometries without the need for extensive sewing.

The bond conditions between knitted textiles and concrete differ significantly from conventional reinforcement methods. Knitted textiles, after coating, form a closed surface, while traditional reinforcement allows concrete to flow through the textile. The bond behavior is influenced by factors such as coating type and yarn texture (Lee et al., 2021).

Various yarns, including hybrid yarns composed of glass and polypropylene filaments, can be used to create knitted fabrics. These materials, especially when using thermoplastic composites, exhibit potential for lightweight applications (Abounaim et al., 2011).

2.5 Cementitious Matrix

In composite materials, the fundamental structure comprises a matrix and reinforcement, each retaining distinct characteristics while significantly influencing the composite's ultimate properties. Matrices can be fabricated from various materials, including polymers, metals, and ceramics. In recent decades, cementitious matrices have garnered attention within the civil engineering sector due to their cost-effectiveness and advantageous attributes such as high compressive strength.

Two main types of cementitious matrices exist: a cement matrix, consisting of cement, sand, and water, and a concrete matrix, which also includes coarse aggregate, water, cement, and sand. For this reason, the mixture composition used in Textile Reinforced Concrete (TRC) is crucial. Concerning textile reinforcement penetration, this is especially important since insufficient penetration might result in decreased efficiency, lowering the tensile strength of TRC relative to the tensile strength of textile reinforcement alone. Improvements in matrix quality can significantly enhance overall composite performance (Alrshoudi, 2015).

2.6 Properties Of Textile Reinforced Concretes

2.6.1 Mechanical properties of TRC

Regarding tensile strength, elastic modulus, stiffness, stability, and application, textile reinforcement differs from other types of reinforcement due to its unique features (Figure 6.1).

TRC surpasses steel reinforcement in several properties. Textile materials, such as AR-glass or carbon, exhibit good resilience to the alkaline environment of concrete, according to Hartig et al. (2008). However, it's essential to note that, while textile reinforcement is superior to steel reinforcement, it is not impervious to environmental factors (Alrshoudi, 2015). Figure 2.12 shows the mechanical properties of various textile materials.

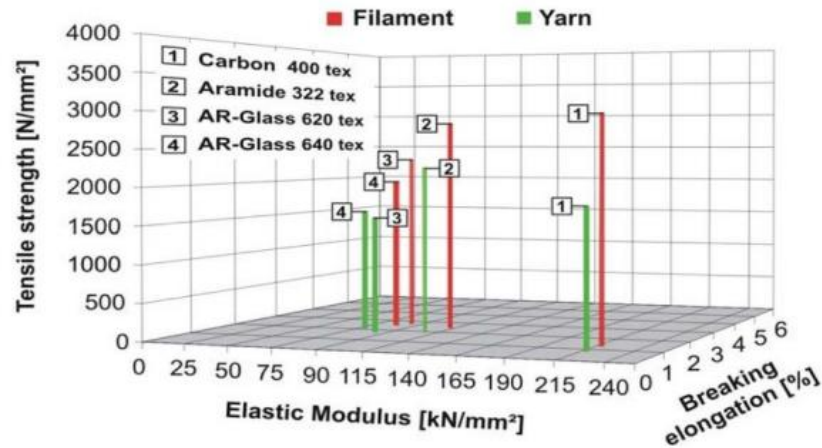


Figure 2. 12: Mechanical properties of various textile materials (Alrshoudi, 2015).

Vignan et al. (2020), conducted experimental tests on compressive, flexural, and impact strengths to investigate the mechanical properties of textile-reinforced concrete (TRC). The results demonstrated that TRC had significantly higher flexural strength than conventional concrete, with an increase of up to 48%. The study also revealed that the number of textile layers in TRC had a substantial effect on its mechanical properties. TRC with a two-layer textile showed the highest flexural and compressive strength, while TRC with a three-layer textile exhibited the lowest strength. This is attributed to the increased textile layers trapping more concrete, reducing its ability to deform and absorb energy.

Textile-reinforced finely-graded cement matrix plates can exhibit a tensile strength improvement of more than 100%. Factors such as the reinforcement ratio, strength of the reinforcement's tensile bond play a crucial role in this enhancement. The inclusion of additional textile layers significantly improves stress distribution throughout the sample volume, reducing the concentration of tensile stress at micro- and meso-scale fracture points.(see Fig. 2.13). However, over-reinforcement may lead to decreased mechanical performance, primarily due to interlaminar shear in areas rich in matrix material or cracks near the clamping zone. It's noteworthy that the tensile strength of the composite is approximately 50% less than that of the individual filaments.

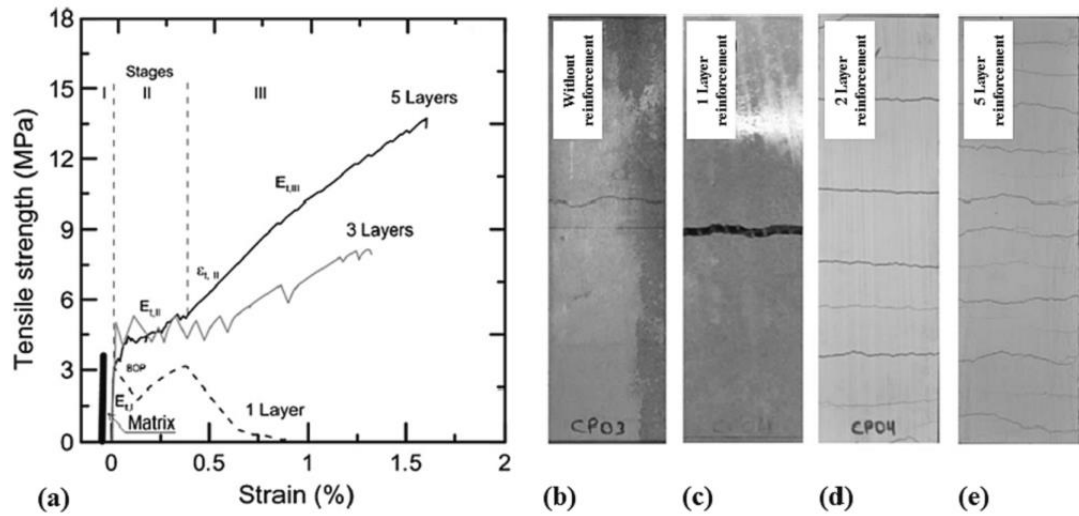


Figure 2. 13: Effect of the number of reinforcement layers on the (a) tensile stress–strain curves, and failure patterns (b) without reinforcement, (c) one, (d) three, and (e) five layers of reinforcement (Rawat et al., 2022).

Figure 2.14 illustrates a comparison of various types of textiles and their corresponding capacities in textile-reinforced concrete. These variations result from the complex mechanism of multifilament failure. Several factors influence a single filament's ultimate load-bearing capacity within the composite, including variations in filament properties, fiber orientation, properties of bonding between roving and the matrix, and the occurrence of faults in specific filaments during manufacture (Alrshoudi, 2015).

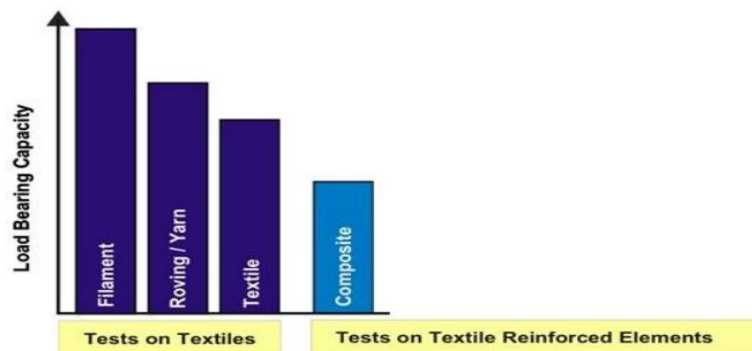


Figure 2. 14: Load bearing capacity of different forms of textile, such as filaments and roving (Alrshoudi, 2015).

2.6.2 Durability of TRC

Durability, in the context of materials and components, refers to their ability to withstand loads without deterioration throughout their service life. When evaluating Textile Reinforced Concrete (TRC) for structural applications, critical durability indicators include long-term tensile capacity, bearing properties in both cracked and non-cracked conditions, and resistance to harsh environments. TRC is widely acknowledged to offer superior durability compared to conventional reinforced concrete (Alma'aitah and Dalalbashi, 2021).

Ensuring the long-term performance of structures using Textile Reinforced Concrete (TRC) involves addressing various issues, from the composite's inherent durability under different environmental influences to its overall contribution. It is crucial to evaluate the chemical stability of reinforcement within the alkaline cementitious matrix to ensure durability. Additionally, the effects of physical processes at the matrix-yarn interface must be considered, as they have the potential to affect bonding over time, with both positive and negative consequences on the mechanical response of the composite. The type of cracking, whether caused by environmental factors such as drying shrinkage and temperature fluctuations or mechanical stress, significantly affects the long-term performance of TRC in structural applications (Peled et al., 2017).

2.6.3 Factors Influencing the Durability and Mechanical Performance

2.6.3.1 Incorporation of Short Fibers

The use of short fibers in Textile-Reinforced Composites has garnered attention due to its ability to enhance the mechanical properties of the matrix, including cracking strength, patterns, and spacing. Proper use of short fibers can improve resilience to frost and high temperatures. However, excessive fiber concentration can adversely affect the viscosity, fiber dispersion, workability, and porosity of concrete (Alma'aitah and Dalalbashi, 2021).

2.6.3.2 Role of additives

TRC matrices primarily consist of cement, fine sand, and water. Studies have explored replacing cement with mineral additions like silica fume and fly ash.. These additives can alter the alkalinity of cement pore solutions, improve self-healing qualities, and increase resistance to alkaline corrosion. Research suggests that combining additives may enhance mechanical characteristics and long-term durability (Alma'aitah and Dalalbashi, 2021).

2.6.3.3 Fabric structure and yarn shape

The fabric structure in cement-based composites, like Textile Reinforced Concrete, significantly affects mechanical properties. Fabric geometry and the forms of individual yarns influence matrix penetration and anchoring strength. (Figure 2.15). Understanding how threads intertwine and their effects on matrix penetration is crucial for optimizing composite performance (Peled et al., 2017).

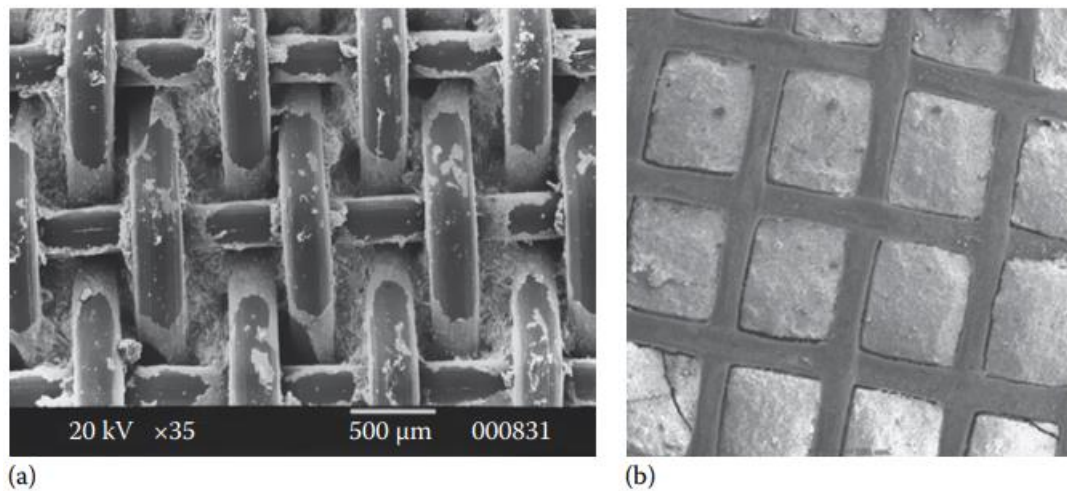


Figure 2. 15: Mechanical anchoring of fabrics embedded in a cement-based matrix: (a) PE plain weave, (b) AR glass bonded (Peled et al., 2017).

As a result, the mechanical properties of composite materials such as textile reinforced concrete and mortars are significantly affected by the fabric structure. To optimize composite performance, it is very important to understand how the threads are intertwined and their effects on matrix penetration (Peled et al., 2017).



3. MATERIALS AND METHODS

In this part of the study, detailed information is given about the production and properties of yarns, the production and mechanical properties of reinforcement fabrics, the measurement methods applied to the fabrics and the evaluation of the results. Additionally, a brief description of the materials and methods used in the application of textile reinforcement materials for the production of textile-reinforced cement-based composites is provided. This section also includes the procedures and tests conducted to determine the mechanical properties of the textile-reinforced cement-based composites.

3.1 Production of Reinforcement Fabric

3.1.1 Yarns used in fabric production

The three different types of yarns made of Dyneema® fiber used in the production of reinforcement fabrics are listed below;

1. Multifilament yarn made from Dyneema® fibers
2. Twisted multifilament yarn made from Dyneema® fibers
3. Friction core-spun yarn; Core part Dyneema® untwisted multifilament yarn, sheath part hemp/polyester staple (%50-%50) fiber

Table 3. 1: Yarn fibers and yarn numbers (dtex).

	Yarn Fiber Type	Yarn Number (dtex)	Yarn Twisting (turns/m)
Warp Yarn	Dyneema®	1760	-
	Twisted Dyneema®	1760	60
	Cored Friction spun yarn Dyneema® Sheath part :%50 Hemp-%50 PES staple fiber	3500-5000*	35-45
Weft Yarn	High Strength PES Multifilament	1670	-

For this purpose, as a first step; multifilament yarns made of Dyneema® fibers with a thickness of 1760 dtex based on high strength polyethylene were provided. Then, for the production of the second type of yarn, the twisting process of the supplied untwisted multifilament yarn was carried out in the Direct Twist machine in Agteks, which is suitable for technical yarns. The determined "k" factor value was used and the $k = 0.8$ value, which corresponds to the $k=0.4-0.9$ range where the strength is the most ideal, was selected (Vlasblom, 2018). Accordingly, 60 turns/mt twist value, which is the most ideal for filament, was used in 1760 dtex. Figure 3.1 shows twisting process in the Direct Twist machine.

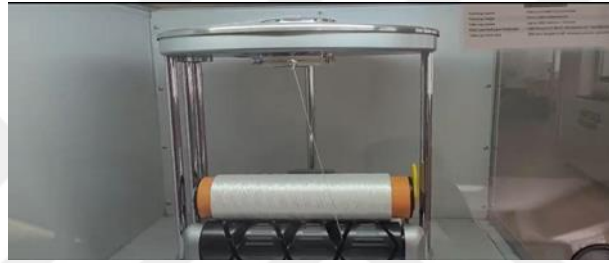


Figure 3. 1: Twisting process on direct twist machine.

Following all pre-experimental productions, the final settings for the Friction spun yarn production machine are provided in Table 3.2 below.

Table 3. 2: Friction spun yarn Production Parameters.

The core fiber linear density and type	1760 dtex Dyneema®
The sheath fiber type	Hemp/PES staple fiber
The number of silver/Silver linear density	4 / Ne 0.120
Production speed	120 m/min
Spinning cylinder speed	4500 turn/min
Opening roller speed	4750 turn/min

Air suction	5000 mbar
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The Friction spinning machine used in the production and produced yarn package are given in Figure 3.2.



Figure 3. 2: Friction spinning machine and produced friction spun yarn.

3.1.2 Weaving Preparation

Initially, attempts were made to weave yarns on the loom without sizing. However, due to the separation of fibers, a proper fabric could not be obtained. Therefore, a suitable sizing agent for the fibers was researched, and a sizing agent named BAYSIZE PES 5-40 was obtained from BayerTeks Textile Chemicals company. Yarns were then sized by transferring them from a single bobbin.

According to the desired warp density value, the yarns were sent to a fabric weaving company in Bursa for warping. At the company, warps of 20 meters in length were drawn for each of the three different yarn types, and using these prepared warps, weaving production of six types of woven fabrics carried out on the Ege University CCI sample weaving machine (Figure 3.3).



Figure 3. 3: CCI sample weaving machine.

3.1.3 Production of Woven Fabrics

Two different fabrics with both plain and twill weave constructions were produced for each yarn type. Initially, single-layer plain weave and single-layer twill (D 2/2 Z) fabrics were produced in the study to determine which woven construction and which warp yarn would give better results (Figure 3.4). The experimental design used in fabric production is given in the table 3.3 below.

Table 3. 3: The experimental plan used in the reinforcement fabric production in the study.

Warp Yarn Sample	Weft Yarn Sample	Weaving Construction (Weave Patterns)	
Dyneema® (W1)	High Strength PES Multifilament (W1)	Plain	Twill
Twisted Dyneema® (W2)			
Friction spun yarn (W3)			

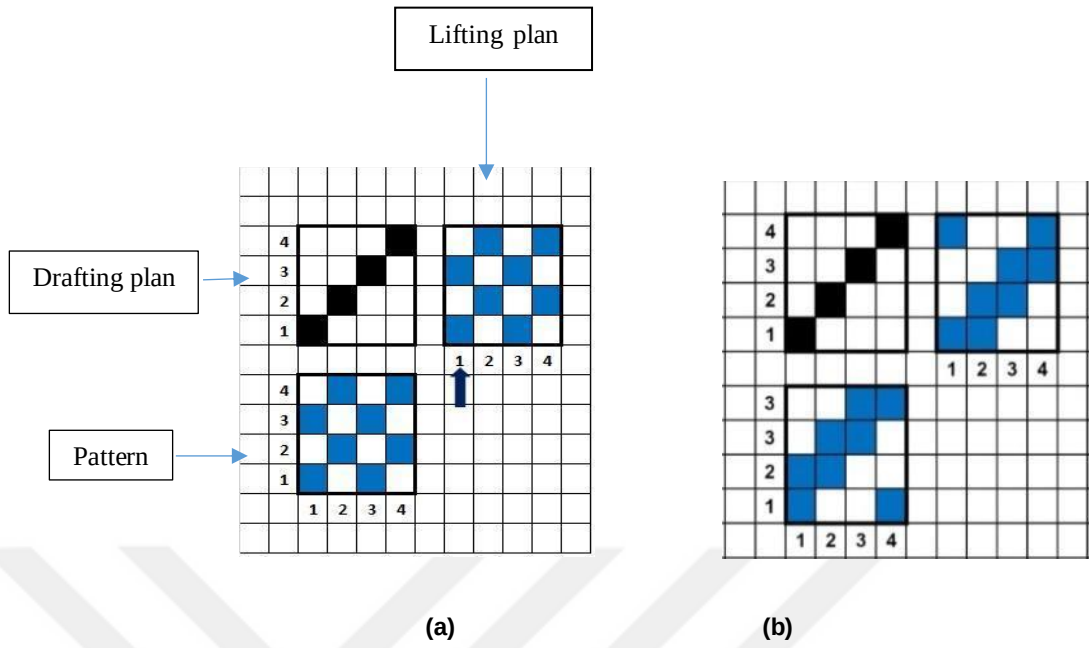


Figure 3. 4: Pattern, draft, and lifting plan for the production of plain (a) and twill (b) woven fabrics.

The production of the planned woven fabrics in the study was carried out on the CCI Sample weaving machine at the Textile Engineering Department of Ege University. Fabric production carried out using Dyneema® yarn. Figure 3.5 below shows images of plain and twill fabrics made from Dyneema®.



Figure 3. 5: Production of dyneema® yarn twill fabric.

The visuals of the production of twisted Dyneema® yarn twill and plain weave are shown in Figure 3.6.

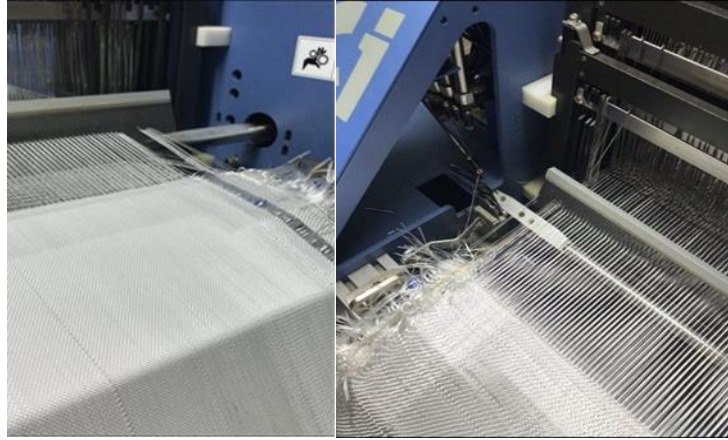


Figure 3. 6: Production of twisted dyneema® yarn plain weave and twill.

Due to challenges encountered during the weaving of Friction spun yarns, carbon reeds were used. (Figure 3.7).



Figure 3. 7: Twill fabric production from friction yarn.

After the production of six types of fabrics for the three different yarns was completed, the fabrics were washed one by one in 90°C water without detergent to remove the sizing material applied to the yarns during the weaving preparation phase. In order to eliminate wrinkles in the washed fabrics, the fabrics were ironed at low temperatures before testing.

3.1.4 Determination of Yarn Type

In the study, 3 different types of yarns made of Dyneema® fiber were used in the production of reinforcement fabrics. These yarns are respectively; Untwisted multifilament yarn made of Dyneema® fibers, twisted multifilament yarn made of Dyneema® fibers and Friction spun yarn whose core part is Dyneema® multifilament and sheath package part is hemp/PES. It was concluded that the yarn with the highest probability of being used as a commercial product in 3 different yarns was the Dyneema®.

Due to issues with Dyneema® yarns separating into fibers and causing defects during weaving, a solution was implemented by wrapping the Dyneema® yarn with polyvinyl alcohol (PVA) staple fiber yarn using a folding machine at Agteks (Figure 3.8). After the production was completed, the woven fabrics were washed once in a 60°C cotton wash program without detergent to completely remove the PVA from the fabric. The warp density values were compared, and it was decided to produce the fabric with a balanced warp and weft density of 6 threads/cm (Figure 3.9).

However, this solution has not been used due to the high cost of PVA yarn.



Figure 3. 8: Winding PVA yarn onto Dyneema® yarn.

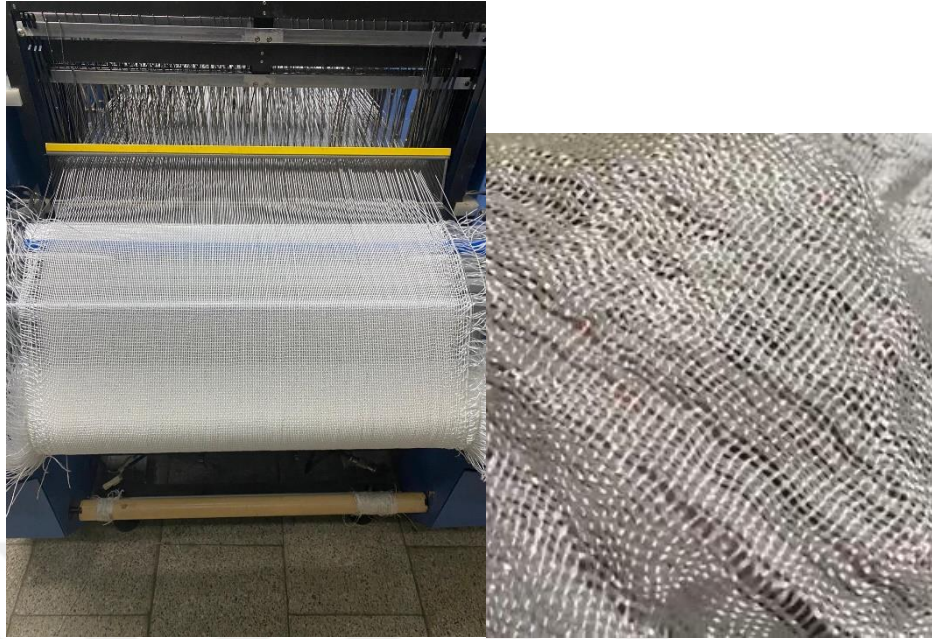


Figure 3. 9: Woven fabric production made with PVA wrapped yarn and fabric appearance after washing.

3.1.5 Determination of Fabric Construction

After deciding on Dyneema® yarn, fabrics produced in two different constructions used in woven fabric production were compared in terms of both the woven fabric production stages and their performance in reinforcement applications. It was concluded that the best weaving construction was plain weave.

3.1.6 Final Woven Fabric Production

After the studies, it was determined that the most suitable yarn for our study is Dyneema® and the fabric structure is plain weaving. However, due to the fact that Dyneema®'s yarn caused problems during weaving, it was decided to pre-twist the yarn at 60 turns /meter as a solution. The images of the fabric produced from pre-spun yarn are shown in Figure 3.10 below. To speed up fabric production and enable the creation of longer lengths of fabric, our yarns were sent to the Numune Dokuma company in Bursa. Subsequently, the production of double-layer and three-layer plain fabrics were carried out at the same company.



Figure 3.10: Woven fabric production with self-twisted Dyneema® yarn and the fabric produced.

For double-layer fabrics, the design patterns, weaving drafts, lifting plans, and sectional views of the plain weave connections used in the study are given in Figure 3.11.

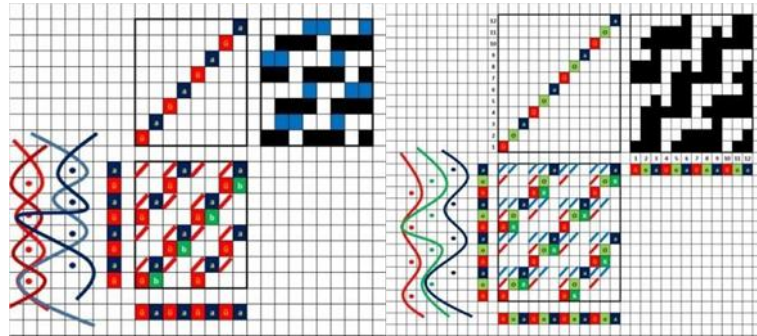


Figure 3.11: Pattern drawing, drafting, lifting plan and section view to be used in the production of two (a) and three layer (b) plain woven fabrics.

After double-layer fabric production, three-layer fabric production was started. The planned pattern drawing was digitized and entered into the computer system of the weaving machine to facilitate the production of three-layer fabrics and the production of 3-layer woven fabric was produced according to this plan. Details of yarn and fabric production experiments are summarized in Table 3.4 below.

Table 3. 4: Experimental plan for yarn and fabric production.

Experimental Plan	Yarn Type	Fabric Construction	Warp Density (ends/cm)	Weft Density (picks/cm)
	Dyneema®	Plain	10	8
		Twill	10	8
	Twisted Dyneema®	Plain	10	8
		Twill	10	8
	Friction spun yarn	Plain	8	8
		Twill	8	8
	Fabric Type	Fabric Construction	Warp Density (ends/cm)	Weft Density (picks/cm)
	Dyneema ®	Plain	6	2
				4
				6
	Double Layer	Plain	6	6
	Three Layer	Plain	6	6

Statistical Analysis

Statistical analysis was performed using one-way ANOVA test. $P < 0.05$ was considered statistically significant.

3.2 Determination Of Physical Properties Of Yarns And Fabrics

3.2.1 Tensile properties of yarns

Before yarn tests, yarn samples were conditioned for 24 hours under standard atmospheric conditions ($20\pm 2^{\circ}\text{C}$ temperature and $65\pm 5\%$ humidity).

The tensile properties of yarns were measured according to TS EN ISO 2062 standard in Zwick/Roell Z010 test device at Textile Research and Applications Center of Ege University (Figure 3.12). For this purpose, yarns of 10-25 cm in length were cut from each of the three different types of yarn. These samples were then subjected to strength tests to evaluate their mechanical properties.



Figure 3. 12: Yarn strength measuring device.

3.2.2 Physical properties of fabrics

Weight in grams, bending resistance, thickness, air permeability, surface friction coefficient and strength properties of 6 types of woven fabrics whose production was completed were tested.

For the weight test, the weight values of the fabrics were measured according to the TS EN ISO 29073-1 standard on the precision balance of the 100 cm² samples taken by cutting 10x10cm square shapes from each fabric type (Figure 3.13). The measurements were repeated 3 times for each fabric type and averaged.



Figure 3. 13: Fabric weight measuring device.

The circular flexural strength of the fabrics was tested in triplicate on the SDL Atlas Digital Pneumatic Stiffness tester in accordance with ASTM D 4032 standard (Figure 3.14). The results were evaluated in Newton (N).

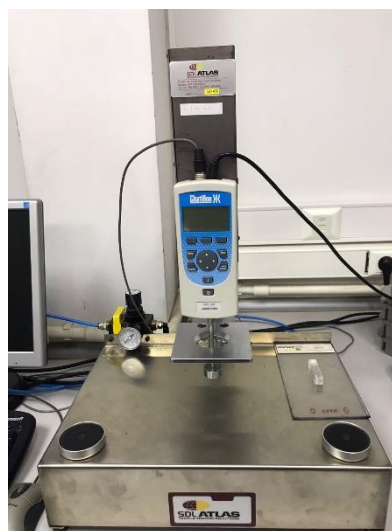


Figure 3. 14: Fabric circular bending strength measuring device.

Fabric thickness is the distance between the top and bottom surfaces between the front and back surfaces. In accordance with TS 7128 EN ISO 5084 standard, the thickness values of the fabrics were measured three times in this study (Figure 3.15).

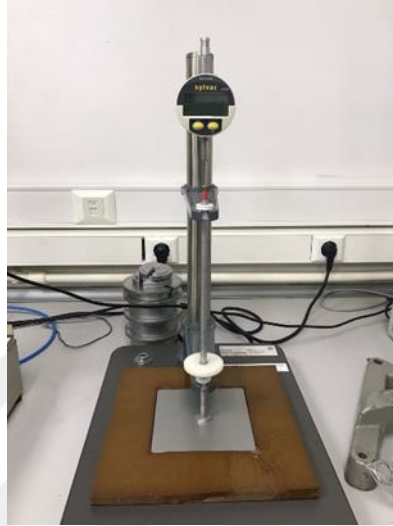


Figure 3. 15: Fabric thickness measuring device.

Air permeability measurement of fabrics was carried out in accordance with TS 391 EN ISO 9237 standard in Textest FX3300 air permeability measurement device (Figure 3.16).



Figure 3. 16: Air permeability measuring device.

The measurement was carried out by pressing the 20 cm² measuring head on the fabric under 100 Pa pressure and the air coming from the compressor passed through the fabric. For each sample, 10 measurements were taken from different parts of the fabric. The values found were averaged and the air permeability of the fabric was determined in l/m² /s.

The strength of the fabrics was measured by cutting three samples, each 25 cm long and 5 cm wide, from each type of fabric. These samples were then tested for strength using the Shimadzu Servopulser 200 kN measuring device (Figure 3.17).



Figure 3. 17: Fabric shrinkage measuring device.

3.3 Production And Testing Of Textile Reinforced Concrete

The cylindrical concrete samples were saturated with water and their surfaces were roughened. The prepared mortar was applied manually to the concrete surface with a spatula to a thickness of 2-3 mm, 180x400 mm fabrics were placed in a single layer, and finally, mortar was again applied to ensure the impregnation and adhesion. In the case of multi-layer applications, the above-mentioned order was followed until the required number of textile layers were applied. However, it has been found that the fabrics of the plain and twill Friction woven type with a warp and weft frequency of 6

x 8 yarn/cm are slightly better embedded in the mortar layer than the fabrics of the Dyneema® woven type with a warp and weft frequency of 10 x 8 yarn/cm.

Compressive strength measurement was carried out in accordance with the TS EN 12390-3 (2019) standard using a Besmak compressive strength testing device (Figure 3.18).

The reinforced cylinders were cured in a chamber containing $\geq 90\%$ relative humidity at 22°C for 24 hours before undergoing a compressive strength test. It has been observed that Friction fabrics show slightly better strength increase compared to Dyneema®, probably due to the fact that it has a lower fabric density rather than the type of fabric.



Figure 3.18: Compressive strength testing device.

Based on these results, fabrics were produced with reduced warp and weft density, and the number of fabric types was reduced to two. Using uncoated Dyneema® plain weave fabric with a density of 6 x 6 ends/picks per cm, reinforcement trials were repeated, with specimens cured for 7 days at 22°C and $\geq 90\%$ relative humidity to allow the mortar to gain strength.

After determining the compressive strength increase rates through reinforcement trials on cylindrical specimens, three-layer beam reinforcement trials were conducted to investigate the flexural strength increase rates using the same fabric types. Flexural strength measurement was carried out in accordance with the TS EN 12390-5 (2019) standard using the ALSA flexural strength testing device (Figure 3.19).



Figure 3.19: Flexural strength testing device.

Reinforcement applications were performed on 100x100x600 mm beam specimens on the bottom (A) surface only (Figure 3.20-3.23) and both bottom and side surfaces (resembling letter covering a span of 400 mm. Sample photographs of reinforced beam and cylinder specimens from the laboratory are presented in Figure 3.24.

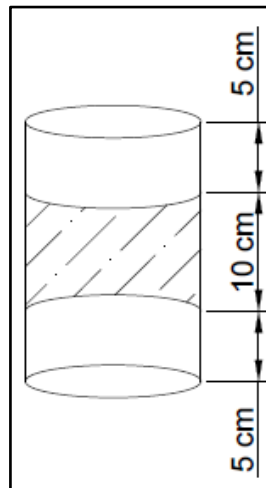


Figure 3. 20: Strengthening the critical middle portion of side surfaces of cylinder samples

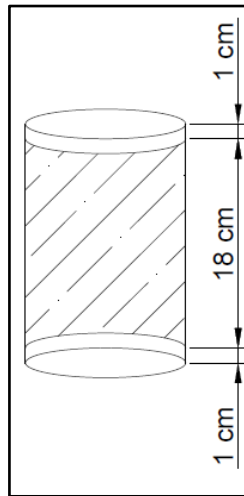


Figure 3. 21: Whole surface strengthening application for cylindrical samples.

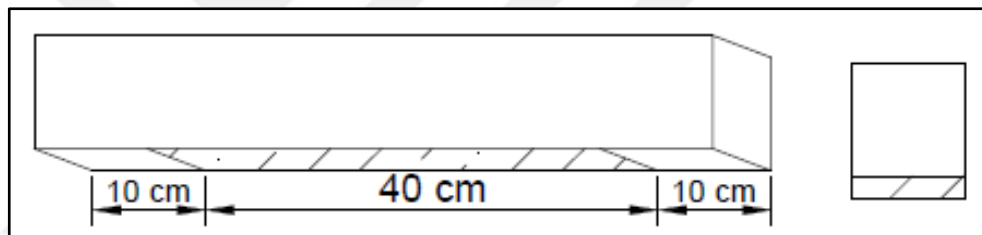


Figure 3. 22: Bottom surface reinforcement application for beam samples.

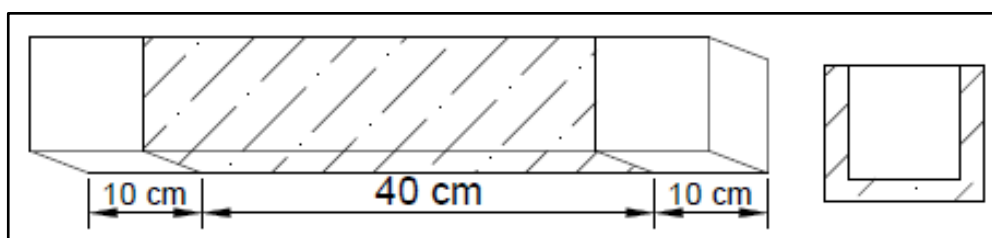


Figure 3. 23: U surface reinforcement application for beam samples.



Figure 3. 24: Strengthening of beam specimens (a), strengthened and tested cylindrical specimens (b).

Following the decision to use plain Dyneema® fabric, the fabrics were cut according to the dimensions of the concrete specimens. For wrapping specimens, the fabrics were cut to 100 mm in height and 400 mm in width with an 85 mm overlap for middle surface applications, and 180 mm in height and 400 mm in width with an 85 mm overlap for full surface applications. For beam specimens, the fabrics were cut to 400 mm in length with 10 mm width for bottom surface applications and 400 mm in length with 30 mm width for U-surface applications.

After cutting, the 28-day water-cured concrete specimens were prepared by roughening their surfaces. Mortar mixtures were then applied to bond the fabrics to the surfaces. In this part, the effects of either 2-, 3- or 4- layers textile application on the enhancement of mechanical properties were investigated (Figure 3.25-27). Following the reinforcement, the specimens were cured in a chamber at $20\pm 2^{\circ}\text{C}$ and $\geq 90\%$ relative humidity for 7 days to allow the mortar to gain strength.



Figure 3. 25: Curing of reinforced cylinder and beam samples.



Figure 3. 26: Reinforced cylinder and beam samples with after curing.

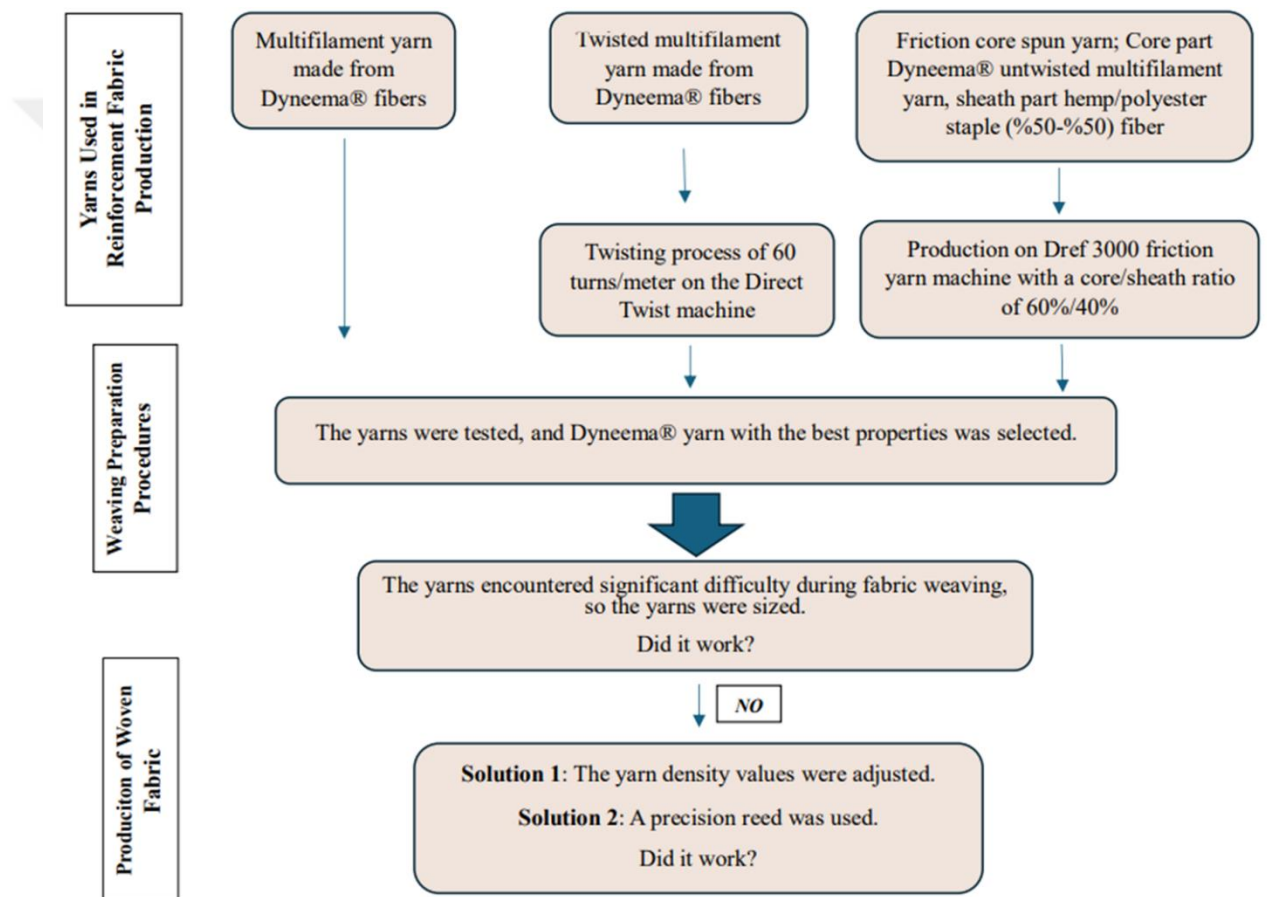


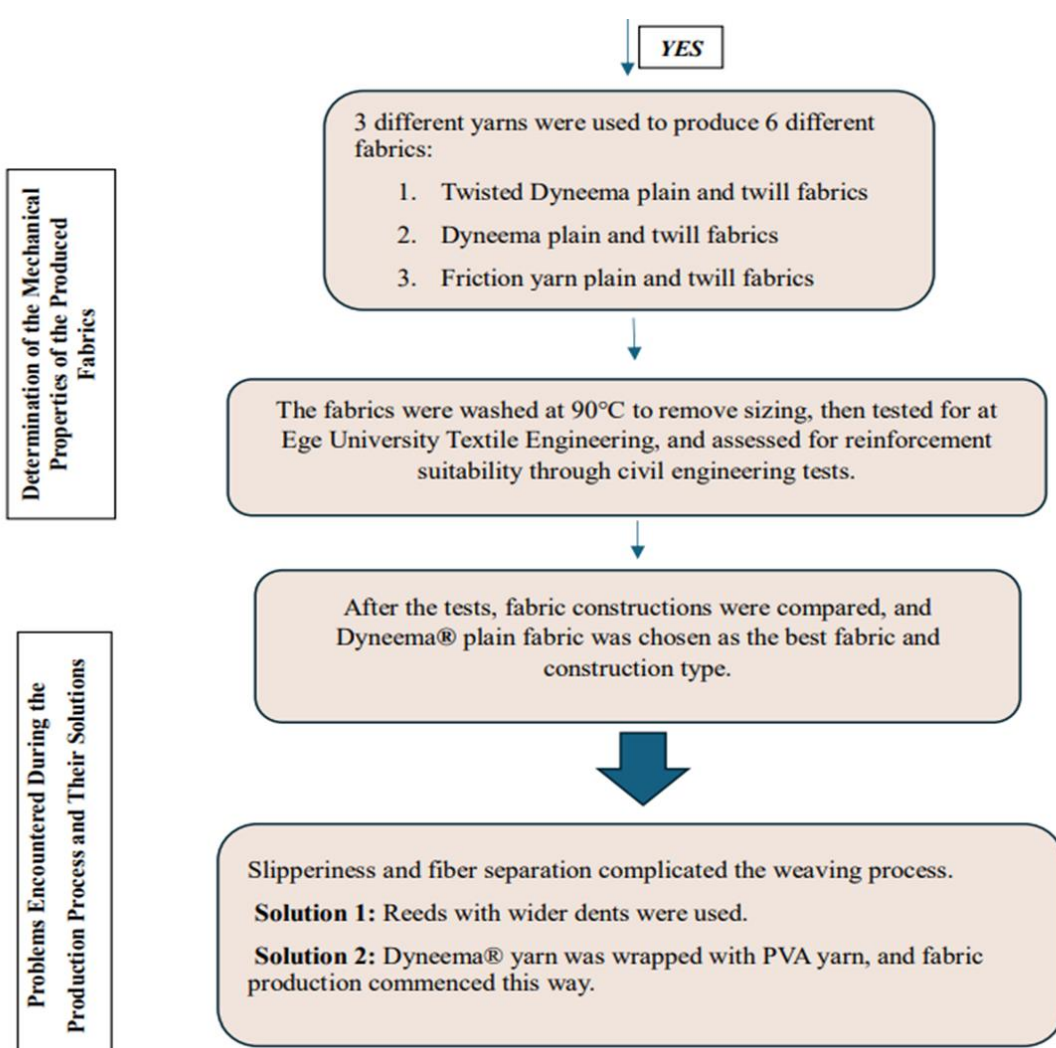
Figure 3. 27: Three-point bending test and deformation measurement applied to reinforced beam samples.

4. FINDINGS AND EVALUATION

4.1 Woven Fabric Production

Below is a schematic diagram summarizing materials and processes used throughout this thesis. This shows the experimental layout used and provides a clear overview of how the workflow of the thesis is executed.





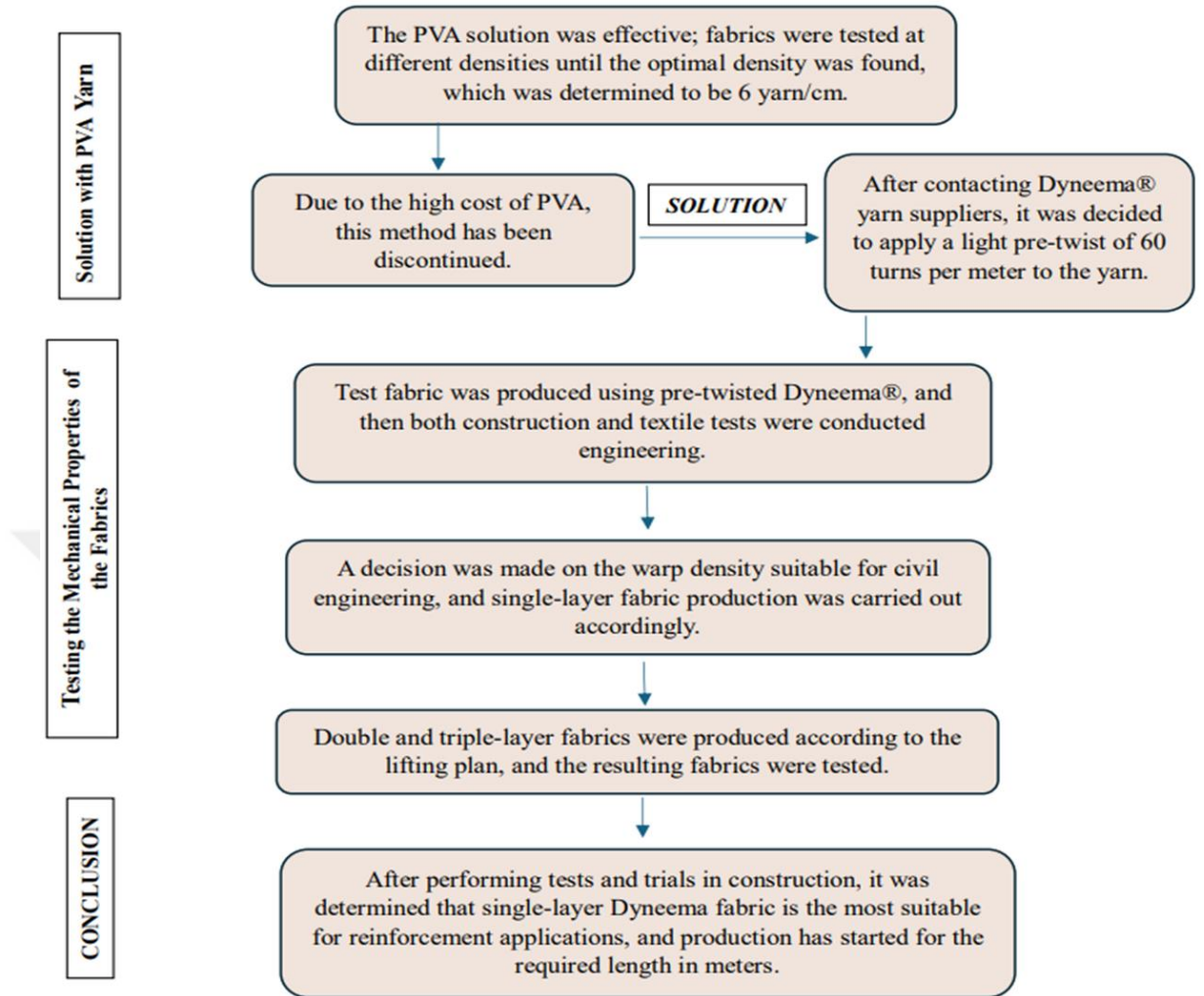


Figure 4. 1: Materials and methods schematic.

Fabric production began initially using Dyneema® yarn. Due to the slippery nature of Dyneema fibers and potential fiber separation during weaving, the weaving speed was deliberately reduced to ensure defects-free fabric production. Following the completion of Dyneema woven fabric production, production commenced with Twisted Dyneema yarn. However, due to its increased slipperiness compared to Dyneema yarn, issues were encountered during fabric production, resulting in occasional gaps in the fabric. Moreover, due to the lower number of yarn interlacings in twill weave compared to plain weave, the twill-produced fabric exhibited more openness and technical issues.

As the third yarn type, friction spun yarn is used in the fabric production. In the core Friction spun yarn, untwisted multifilament yarns made of Dyneema® fibers are used in the core part of the yarn, and hemp/polyester (%50/50) fibers are used in the sheath part. Hemp has been preferred to contribute to the improvement of fiber-matrix adherence by providing better penetration of the mortar to be used in strengthening the fibers. The highest possible hemp ratio produced with 50% Hemp/50% Polyester staple fibers could be supplied from Karacasu Tekstil in II. Passage Draw Frame sliver form with Ne 0.120 linear density. Later, Friction spun yarn production was carried out on the Friction 3000 friction spun yarn machine in Raper Medical Textile company in Uşak. The Friction spinning machine used in the production and the most recently produced.

Preliminary trials were conducted to determine the optimal core/sheath ratio before commencing full-scale production. Based on these pre-experiments, the production parameters were finalized, resulting in a core/sheath ratio of 60%/40%, ensuring that the fibers in the sheath were fully covered by the filament in the core.

Subsequently, fabric production was carried out using Friction spun yarns. During the weaving of Friction spun yarns, the thick tine of the reed began to separate the hemp fibers wrapped around the Dyneema yarn due to its thick nature. This issue caused irregularities in the fabric, resulting in protrusions in certain areas. To address this, a special carbon reed with wider intervals replaced the weaving reed, resolving the issue.

After determining Dyneema as the most suitable yarn for the study, fabric production began with multi-layer fabrics. To prevent fabric defects due to the slippery nature of Dyneema yarn, Dyneema yarns were wrapped with PVA yarns. This method ensured smooth fabric production.

Warp density values determined after the calculations made for 3 different yarn types are given in the Table 9.2 below. Weft density was determined as 8 picks/cm weft density.

Table 4. 1: Warp and weft densities of the fabrics used in the production.

Yarn Type	Warp Yarn Linear Density (dtex)	Target Warp Density (ends/cm)	Final Warp Density (ends/cm)	Weft Yarn Linear Density (dtex)	Weft Density (picks/cm)
Dyneema®	1760	10	10	1100	8
Twisted Dyneema®	1887	10	10		
Friction spun yarn	2932	8	6		

Following the completion of fabric production, density tests were conducted to create gaps in the fabric for the mortar used in reinforcement. Initially, various warp density values were tested for this purpose. As reinforcement was primarily in the warp direction, significantly reducing this density would diminish the fabric's contribution to reinforcement. Therefore, the warp density value was set at the previously used 6 ends per centimeter, allowing mortar to pass through the fabric without hindrance. After determining the warp density, fabrics were woven using different weft densities (2, 4, and 6 picks per centimeter) to achieve the required gap width for mortar passage.

Experimental results indicated that with weft densities of 2 and 4 picks per centimeter, the fabric exhibited non-uniform gaps and loose structure, posing challenges during reinforcement application and compromising fabric stability. Consequently, a weft density of 6 picks per centimeter was determined to maintain both sufficient gap width and fabric stability. Thus, it was decided to produce balanced fabrics with a warp and weft density of 6 ends per centimeter and 6 picks per centimeter, respectively.

To address issues such as fiber splitting during fabric production, Dyneema® yarn was wrapped with PVA yarn. However, due to the additional wrapping process and the high cost associated with PVA yarn, not all planned fabrics could be produced

using the PVA wrapping method described in this study. Consequently, to mitigate issues encountered during weaving, it was decided to apply a light pre-twist (60 turns per meter) to the yarn by collaborating with Dyneema® yarn suppliers abroad. A test sample was produced, and since the woven fabric exhibited the desired properties, it was decided to apply the same twisting process to the remaining yarns.

To expedite production and broaden fabric applications, the yarns sent to the Sample Weaving company in Bursa were twisted at this facility. Following the trials, single-layer, double-layer, and triple-layer fabrics with a plain weave structure, suitable for the planned weave pattern, were produced. The optimal interlacing of warp and weft yarns resulted in high strength properties.

4.2 Properties of Yarns and Fabrics

4.2.1 Yarn breaking strength and breaking elongation

The breaking strength values of three different yarn types are illustrated in Figure 4.2, while the breaking elongation values are shown in Figure 9.3. According to these values, the highest strength was obtained with Twisted Dyneema® yarn, which measured 22.13 cN/dtex. Dyneema® followed closely with a strength value of 22.8 cN/dtex, and the lowest strength value was observed in friction spun yarns, which registered 8.96 cN/dtex. These results indicate that the twist applied to Dyneema® yarn significantly enhances its strength by improving the adhesion between fibers.

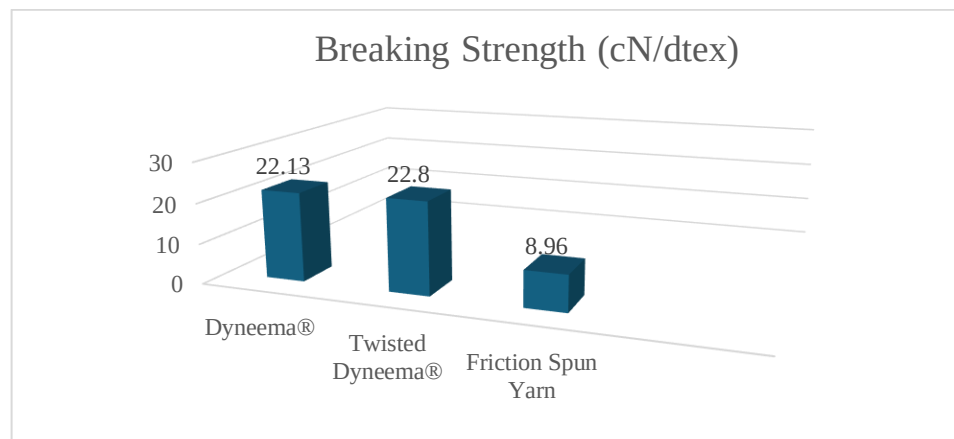


Figure 4. 2: Yarn breaking strength values.

Yarn breaking strength values are also given in Table 4.2 .

Table 4. 2: Yarn breaking strength values.

Yarn Type	Breaking Strength (cN/dtex)
Dyneema®	22.13
Twisted Dyneema®	22.8
Friction spun yarn	8.96

The breaking elongation percentages further reveal the performance characteristics of these yarns. Twisted Dyneema® exhibited a breaking elongation of 2.46%, Dyneema® 3.52%, and Friction spun yarn 5.39%. The higher elongation rate of the Friction spun yarn can be attributed to the inclusion of staple fibers in its sheath, which possess inherently high elongation properties (Figure 4.3).

The comparatively low breaking strength of the Friction spun yarns necessitated a deeper analysis to understand the underlying reasons. The primary hypothesis was that the low strength values were due to the high elongation properties of the staple fibers in the sheath part of the yarn, combined with potential deformation of Dyneema® fibers due to friction and heating against machine elements during the Friction spun yarn production process.

To test this hypothesis, the sheath part of the Friction spun yarn was eliminated, and the core part (Dyneema®) was tested separately. The strength of the core Dyneema® yarn was determined to be 20.46 cN/dtex, and the breaking elongation percentage was found to be 3.15%. These values confirm that the core Dyneema® yarn itself has a significantly higher strength than the Friction spun yarn as a whole. The reduced strength in the Friction spun yarn can be attributed to the staple fibers in the sheath, which not only exhibit high elongation but also potentially weaken the overall yarn structure.

Additionally, the process of producing Friction spun yarn involves considerable friction and heating, which likely causes deformation in the Dyneema® fibers. This mechanical stress during production can compromise the inherent strength of Dyneema® fibers, leading to the observed reduction in breaking strength.

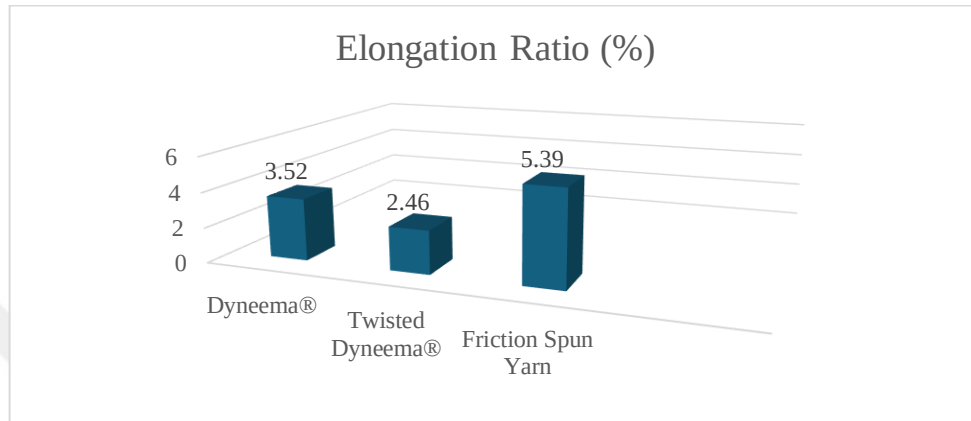


Figure 4. 3: Percentage values of yarn breaking elongation.

Percentage values of yarn breaking elongation are also given in Table 4.3.

Table 4. 3: Percentage values of yarn breaking elongation.

Yarn Type	Elongation Ratio (%)
Dyneema®	3.52
Twisted Dyneema®	2.46
Friction spun yarn	5.39

The breaking elongation percentages further reveal the performance characteristics of these yarns. Twisted Dyneema® exhibited a breaking elongation of 2.46%, Dyneema® 3.52%, and Friction spun yarn 5.39%. The higher elongation rate of the Friction spun yarn can be attributed to the inclusion of staple fibers in its sheath, which possess inherently high elongation properties.

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Additionally, the process of producing Friction spun yarn involves considerable friction and heating, which likely causes deformation in the Dyneema® fibers. This mechanical stress during production can compromise the inherent strength of Dyneema® fibers, leading to the observed reduction in breaking strength.

4.2.2 Fabric Thickness

The thickness measurements of six different fabrics produced from three different yarn types were evaluated, revealing significant insights into the structural properties of the fabrics. The data indicated that twill fabrics exhibited greater thickness compared to plain fabrics, a phenomenon attributable to the increased number of folds in twill weave patterns. This relationship is illustrated in Figure 4.4 and is further substantiated by the specific thickness values observed in the study.

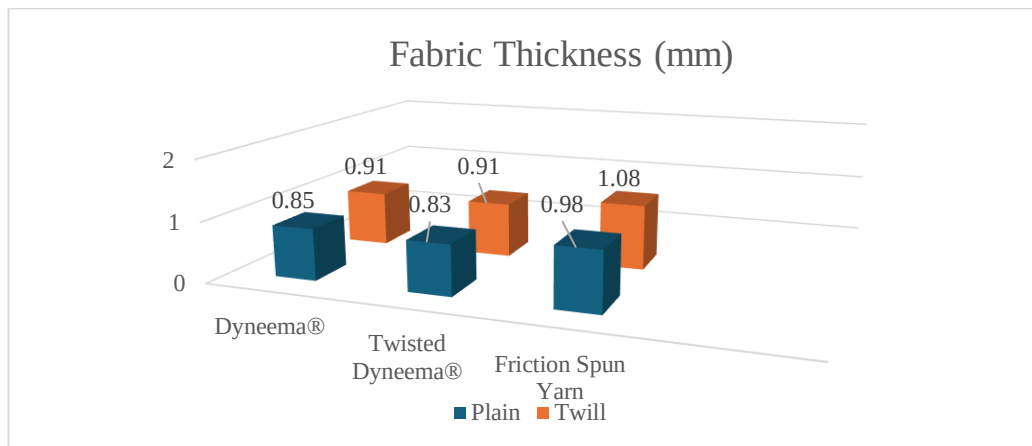


Figure 4. 4: Thickness values of woven fabrics with different yarn types and weave patterns.

For twisted Dyneema® yarn, the plain fabric showed a thickness of 0.83 mm, while the twill fabric was thicker at 0.91 mm. Similarly, fabrics made from Dyneema® displayed a plain weave thickness of 0.85 mm, with the twill weave reaching the same thickness as the twisted version at 0.91 mm. The most notable difference was observed in the Friction spun yarn, where the plain fabric had a thickness of 0.98 mm, and the twill fabric was measured at 1.08 mm.

The greater thickness in twill fabrics compared to plain fabrics can be attributed to the nature of the twill weave, which involves overlapping yarns in a manner that creates diagonal ridges. These ridges result in additional layers of yarn within the fabric structure, thereby increasing the overall thickness. This characteristic is particularly advantageous in applications where additional bulk and texture are desired.

Fabric thickness values are also given in Table 4.4.

Table 4. 4: Fabric thickness values.

Fabric Type	Fabric Construction	Thickness (mm)
Dyneema®	Plain	0.85
	Twill	0.91

Twisted Dyneema®	Plain	0.83
	Twill	0.91
Friction spun yarn	Plain	0.98
	Twill	1.08

When further examining fabric thickness, the thickness values of Dyneema® fabrics in different layer configurations were analyzed (Figure 4.5). The plain single-layer Dyneema® fabric was measured at 0.52 mm. When configured into a plain double layer, the thickness increased to 0.61 mm, and a plain three-layer fabric reached 0.63 mm. These measurements demonstrate a progressive increase in fabric thickness with additional layers, highlighting the impact of fabric construction on the final material properties.

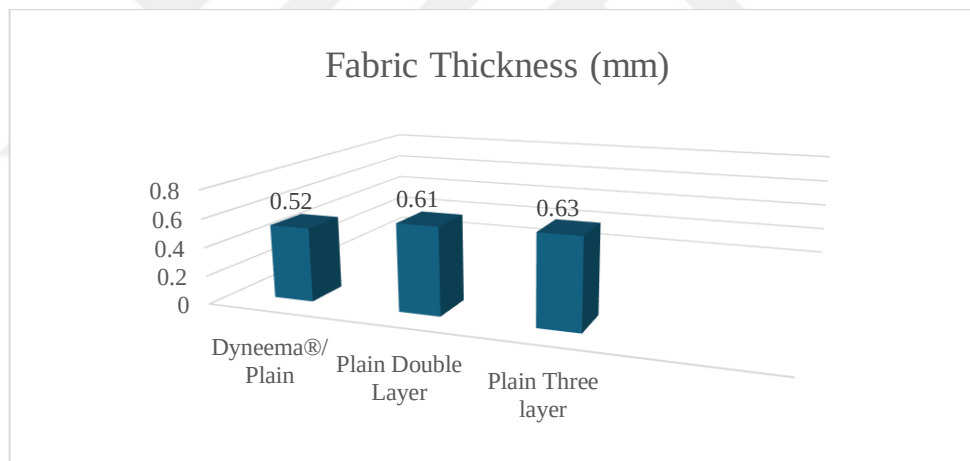


Figure 4. 5: Thickness values of layered fabrics.

Fabric thickness values of layered fabrics are also given in Table 4.5.

Table 4. 5:: Thickness values of layered fabrics.

Fabric Type	Thickness (mm)
Dyneema® / Plain	0.52
Plain Double Layer	0.61
Plain Three Layer	0.63

4.2.3 Fabric Weight

When the fabric thicknesses were evaluated, it was determined that the highest value was the Dyneema®. This can be explained by the fact that there are more connections in the plain weave construction and that the Dyneema® yarn causes fewer defects in the fabric compared to other yarns during fabric production.

On the other hand, it was observed that plain twisted Dyneema® and Friction spun yarn twill fabrics had the lowest weight values (Figure 4.6). These two fabric types experienced the most problems during production, resulting in more defects compared to other fabrics. Since these defects cause occasional openings in the fabrics, it has been determined that the weight values are lower.

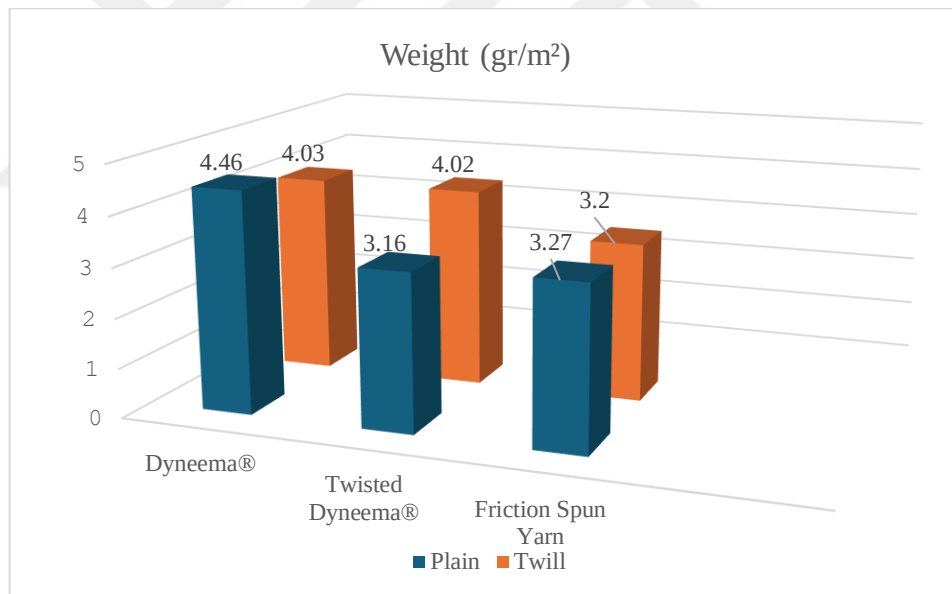


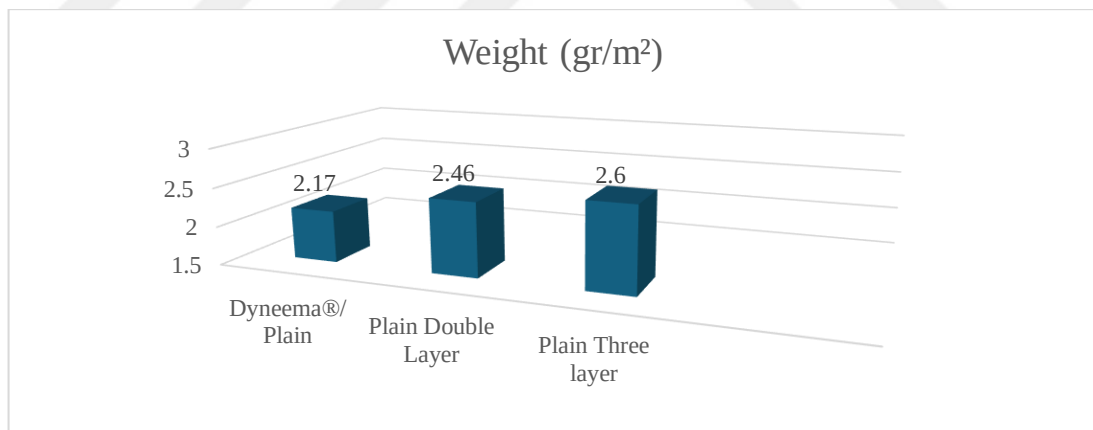
Figure 4. 6: Weight values of woven fabrics with different yarn types and weave patterns.

Weight values are also given in Table 4.6.

Table 4. 6: Weight values of fabrics.

Fabric Type	Fabric Construction	Weight (gr/m ²)
Dyneema®	Plain	4.46
	Twill	4.03
Twisted Dyneema®	Plain	3.16
	Twill	4.02
Friction spun yarn	Plain	3.27
	Twill	3.20

As can be seen in the figures, when the weight values of the layered fabrics were measured, the highest value was observed in the three-layer plain Dyneema® fabric. This increase in weight can be attributed to the higher amount of yarn used in the fabric, which increases the overall weight (Figure 4.7).

**Figure 4. 7:** Weight values of layered fabrics.

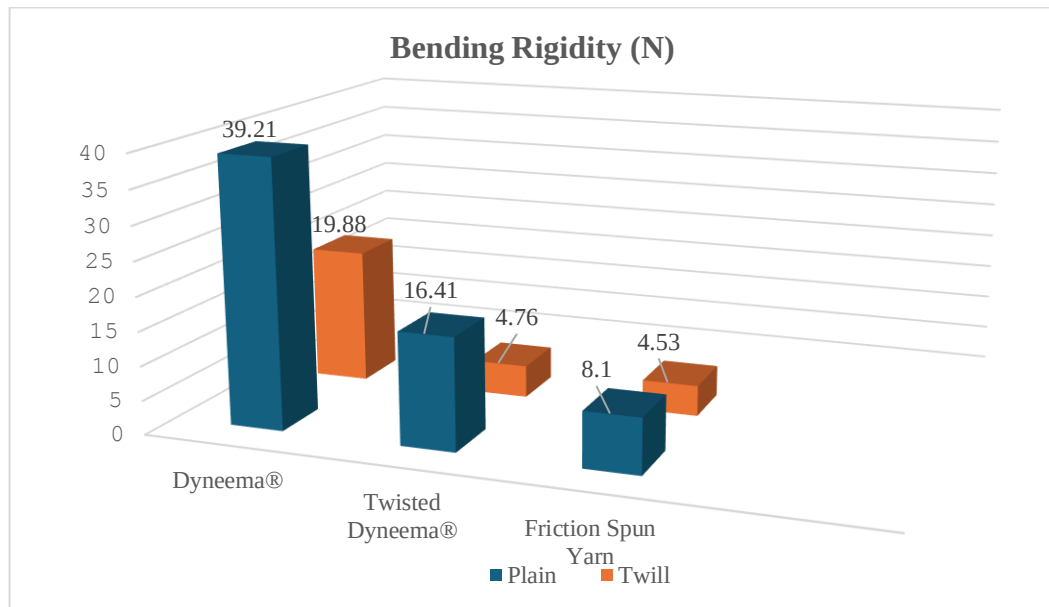
Weight values of layered fabrics are also given in Table 4.7.

Table 4. 7: Weight values of layered fabrics.

Fabric Type	Weight (gr/m ²)
Dyneema® / Plain	2.17
Plain Double Layer	2.46
Plain Three Layer	2.60

4.2.4 Fabric Bending Rigidity

When comparing the bending strength values of the fabrics, it is evident that the highest value was recorded in fabrics made from Dyneema yarns, followed by those woven from twisted Dyneema® and Friction spun yarns, respectively. This trend underscores the influence of yarn type on the bending stiffness of the fabrics. Interestingly, the impact of woven fabric structure on bending stiffness appears consistent across all three yarn types. Notably, plain weave fabrics exhibit higher bending strength values compared to twill weave fabrics due to their higher number of interlacements, which enhances structural integrity (Figure 4.8).

**Figure 4. 8:** Bending strength comparison of fabrics by yarn type and weave structures.

Bending rigidity comparison of fabrics by yarn type and weave structures are also given in Table 4.8 .

Table 4. 8: Bending rigidity results.

Fabric Type	Fabric Construction	Bending Rigidity (N)
Dyneema®	Plain	39.21
	Twill	9.88
Twisted Dyneema®	Plain	16.41
	Twill	4.76
Friction spun yarn	Plain	8.10
	Twill	4.53

4.2.5 Air permeability

When the results of air permeability tests are evaluated, it becomes clear that the structure of woven fabrics plays a critical role in determining the air permeability properties. Generally, plain weave fabrics exhibit lower air permeability values than twill weaves due to the higher density of interlacing. This denser structure restricts airflow more effectively, as seen in Figure 4.9-4.10 below.

The effect of yarn twist on air permeability is particularly noticeable. Fabrics woven from twisted yarns tend to have higher air permeability values; this is especially evident in plain weave structures where the twist creates additional spaces for air to pass through. Although this phenomenon is present in both plain and twill weaves, it varies more significantly in plain weave fabrics.

Fabrics produced with Friction spun yarns were found to have the highest air permeability values among the tested materials.

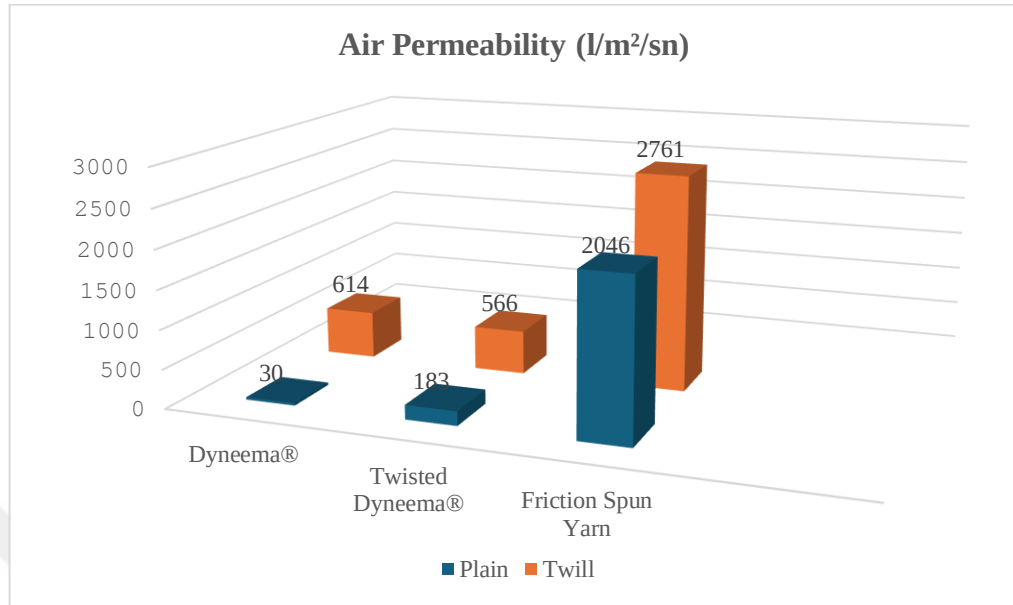


Figure 4. 9: Air permeability values of woven fabrics with different yarn types and weave patterns.

Air permeability values of fabrics are also given in Table 4.9.

Table 4. 9: Air permeability values of woven fabrics.

Fabric Type	Fabric Construction	Air Permeability (l/m²/sn)
Dyneema®	Plain	30
	Twill	614
Twisted Dyneema®	Plain	183
	Twill	566
Friction spun yarn	Plain	2046
	Twill	2761

Layering complicates the fabric structure, altering the flow of air through the material. Based on the data, it is observed that plain single-layer fabric had lower air permeability values compared to double-layer plain Dyneema® and three-layer plain Dyneema® structures.

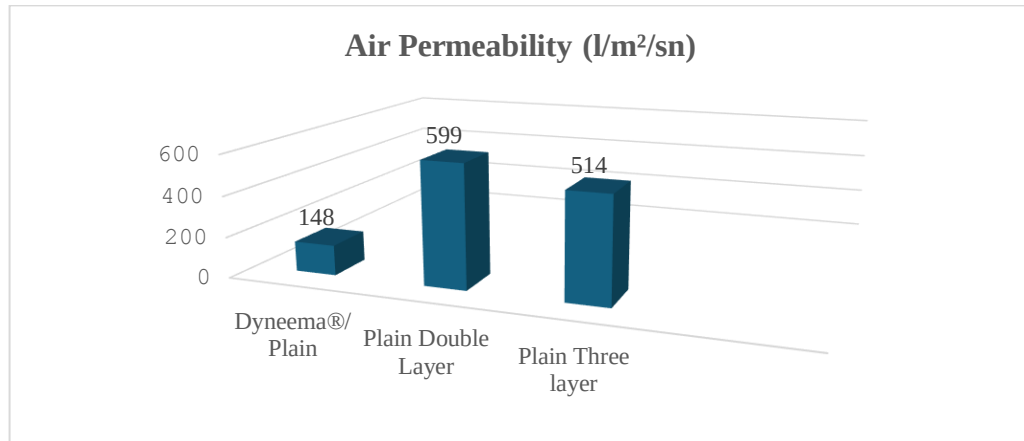


Figure 4. 10: Air permeability values of layered woven fabrics.

Air permeability values of layered woven fabrics are also given in Table 4.10.

Table 4. 10: Air permeability values of layered woven fabrics.

Fabric Type	Air Permeability (l/m²/sn)
Dyneema® / Plain	148
Plain Double Layer	599
Plain Three Layer	514

4.2.6 Fabric breaking strength and elongation

In evaluating the strength and elongation properties of woven fabrics, significant variations were observed based on yarn type and fabric structure. Fabrics woven from twisted Dyneema® yarns demonstrated the highest elongation rates, attributed to the increased yarn mobility facilitated by the twist. This effect was most pronounced in plain weave constructions, where the yarn twist allows for greater deformation under stress. The plain weave Dyneema® fabric exhibited the highest strength at 241.15 MPa, while the twill weave Dyneema® fabric had a lower strength of 173.69 MPa. Friction spun yarn fabrics had the lowest strength, with plain weave at 102.80 MPa and twill weave at 77.2 MPa (Figure 4.11).

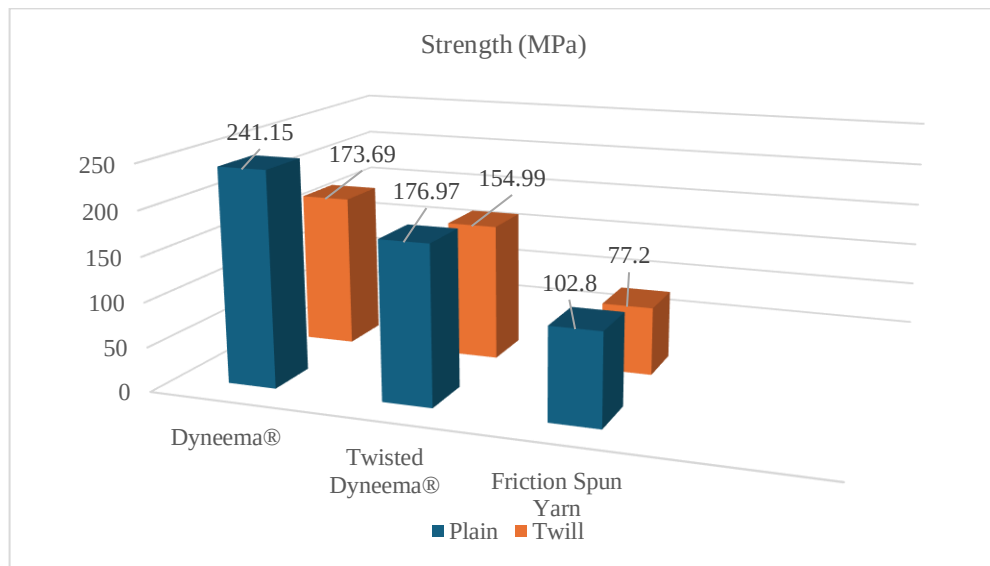


Figure 4. 11: Strength values of woven fabrics with different yarn types and weave patterns.

Strength values of woven fabrics with different yarn types and weave patterns are also given in Table 4.11.

Table 4. 11: Strength values of woven fabrics.

Fabric Type	Fabric Construction	Breaking Strength (MPa)
Dyneema®	Plain	241.15
	Twill	173.69
Twisted Dyneema®	Plain	176.97
	Twill	154.99
Friction spun yarn	Plain	102.80
	Twill	77.2

Layer configuration also affected strength, with the double-layer plain weave Dyneema® fabric reaching 233 MPa, higher than the single-layer at 169 MPa. It was observed that layered fabric structures, such as double and three layers in plain weave, reduce elongation rates while maintaining strong tensile properties. The double-layer plain weave exhibited a strength of 233 MPa and an elongation of 6.32%,

demonstrating the balance between structural integrity and flexibility in multilayer textiles (Figure 4.12).

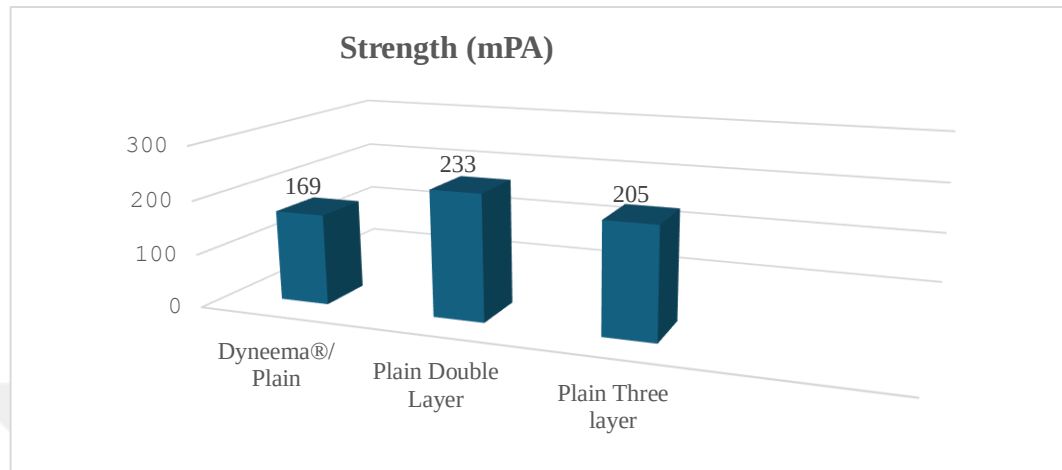


Figure 4. 12: Strength values of layered fabrics.

Strength values of layered fabrics are also given in Table 4.12.

Table 4. 12: Strength values of layered fabrics.

Fabric Type	Breaking Strength (MPa)
Dyneema® / Plain	169
Plain Double Layer	233
Plain Three Layer	205

The data shows that Twisted Dyneema® fabrics have the highest elongation ratios, especially in plain weave construction. This indicates that these fabrics are more flexible compared to other fabric types. Conversely, Dyneema® fabrics in twill weave exhibit lower elongation compared to those in plain weave. Friction spun yarn fabrics show intermediate elongation values, with slightly higher elongation in plain weave compared to twill weave (Figure 4.13).

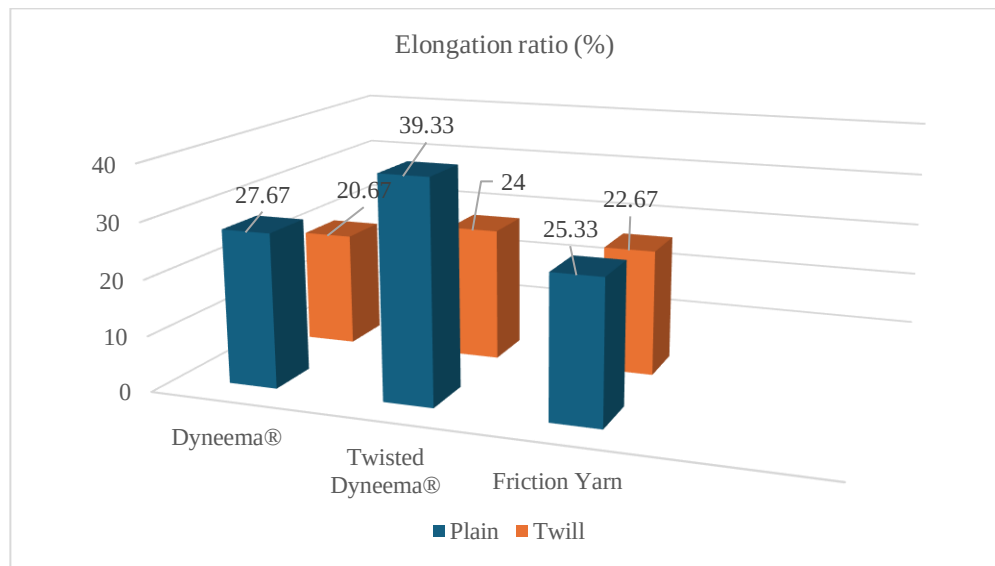


Figure 4. 13: Elongation ratio values.

Elongation ratio values are also given in Table 4.13.

Table 4. 13: Elongation ratio values.

Fabric Type	Fabric Construction	Elongation ratio (%)
Dyneema®	Plain	27.67
	Twill	20.67
Twisted Dyneema®	Plain	39.33
	Twill	24.00
Friction spun yarn	Plain	25.33
	Twill	22.67

These results indicate that Dyneema® yarn has the highest elongation ratio among the tested yarn types, reflecting its greater flexibility. In contrast, both Plain Double Layer and Plain Three Layer yarns show lower elongation ratios, with the Plain Three Layer yarn exhibiting slightly higher elongation than the Plain Double Layer yarn (Figure 4.14).

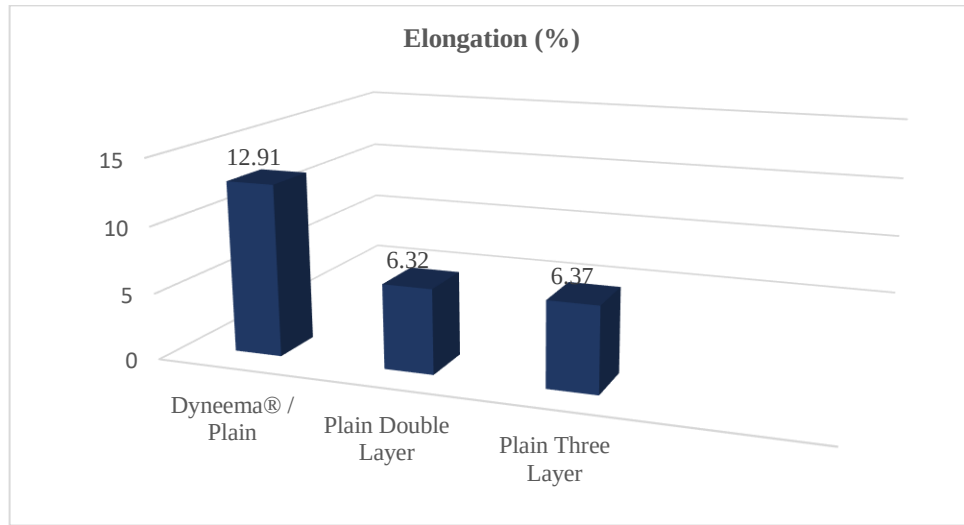


Figure 4. 14: Elongation ratio values of layered fabrics.

Elongation ratio values of layered fabrics are also given in Table 4.14.

Table 4. 14: Elongation ratio values of layered fabrics.

Yarn Type	Elongation Ratio (%)
Dyneema®	12.91
Plain Double Layer	6.32
Plain Three Layer	6.37

Statistical Analysis

Upon examining the obtained test results, it has been determined that the type of yarn and the weaving construction significantly affect the fabric properties such as thickness, breaking strength, breaking elongation ratio, air permeability, bending resistance a statistical standpoint (Table 4.15).

Table 4. 15: Fabric test results.

Source of Variance	Fabric Property	Sum of Square	F value	Sig.
Yarn Type	Thickness	0.153	25.47	.000*
	Tensile Strength	42838.87	84.51	.000*
	Elongation at Break	230.11	8.40	.000*
	Air Permeability	5.634E7	1157.86	.000*
	Bending Resistance	1840.47	44.02	.000*
Fabric Construction	Thickness	0.049	16.21	.000*
	Tensile Strength	6534.91	25.78	.000*
	Elongation at Break	312.50	22.82	.000*
	Air Permeability	4716384.14	193.84	.000*
	Bending Resistance	600.31	28.72	.000*

It was observed that as the number of fabric layers increased, the fabric thicknesses also increased proportionally. When the average strength values of the fabrics were examined, the highest strength was obtained in the double-layered fabric, while the lowest strength was observed in the single-layered fabric. Due to the high variation in the strength test values of the layered fabrics, the statistical analysis conducted found that the effect of the number of fabric layers on the fabric breaking strength was insignificant (Table 4.16).

Table 4. 16: The fabric test results were evaluated using two-way analysis of variance.

Source of Variance	Fabric Property	Sum of Squares	F value	Sig.
Fabric Layers Count	Thickness	0.032	7.35	.000*
	Tensile Strength	6248.15	4.55	.000*
	Elongation at Break	86.37	60.05	.000*
	Air Permeability	1146866,06	382,82	,000*

4.3 Properties Of Textile Reinforced Concretes

This section presents the results of the experimental work conducted by the Civil Engineering Department of Ege University as part of the TUBITAK project.

Initially, in order to determine the effect of six different fabric types on the compressive strength of concrete the entire surface of cylindrical concrete samples was wrapped with a single layer of each fabric. Table 4.17 presents the compressive strength and strength increase rates for single-layer reinforced cylinder specimens. The results show that friction spun yarn reinforcement led to the highest strength increases compared to control concrete, with a 4.69% increase for plain surfaces and 2.28% for twill surfaces. In comparison, Dyneema® fabrics offered only minimal improvements in compressive strength, with twill weaves showing slightly better performance than plain weaves, though the differences were not statistically significant.

It was noted that fabrics from friction spun yarn provided somewhat greater strength increases compared to Dyneema® fabrics. This is thought to be due to the fact that, irrespective of the fabric type, fabrics made from friction spun yarn have lower fiber densities compared to Dyneema® fabrics.

Table 4. 17: Compressive strength and strength increase rates for single-layer reinforced cylinder specimens.

Fabric Used for Reinforcement and Reinforcement Type	Compressive Strength (MPa)		Strength Increase Compared To Control (%)
	Reinforced Concrete	Control Concrete	
Dyneema® Plain (Full Surface)	34.98	35.15	-
Twisted Dyneema® Plain (Full Surface)	34.20	35.15	-
Dyneema®	34.50	35.15	-

Twill (Full Surface)			
Twisted Dyneema® Twill (Full Surface)	35.46	35.15	0.88
Friction spun yarn Plain (Full Surface)	36.80	35.15	4.69
Friction spun yarn Twill (Full Surface)	35.95	35.15	2.28

Based on the experience gained from the reinforcement application of fabrics in a single layer on cylindrical samples, new fabrics were produced by reducing the warp and weft densities of the fabrics. This plain weave Dyneema® fabric with a warp and weft density of 6 x 6 threads/cm was wrapped around the concrete samples in two and three layers. Tables 4.18 and 4.19 present the compressive strengths and strength increase rates for samples reinforced with two and three layers, respectively. The results indicate that two-layer and three-layer reinforcements provided more significant strength increases compared to single-layer reinforcements. For two-layer and three-layer reinforcements using un-twisted Dyneema® fabric, the strength increase rates were 9.94% and 34.42%, respectively. In contrast, for two-layer and three-layer reinforcements using the fabric from friction spun yarn, the strength increase rates were 4.96% and 11.69%, respectively. In both fabric types, the strength increase rates significantly improved with the increase in the number of reinforcement layers.

Table 4. 18: Compressive strength and strength increase rates for two-layer reinforced cylinder specimens.

Fabric Used for Reinforcement and Reinforcement Type	Compressive Strength (MPa)		Strength Increase Compared To Control (%)
	Reinforced Concrete	Control Concrete	

Dyneema® Plain (Full Surface)	44.15	40.16	9.94
Friction spun yarn Plain (Full Surface)	42.15	40.16	4.96

Table 4. 19: Compressive strength and strength increase rates for three-layer reinforced cylinder specimens.

Fabric Used for Reinforcement and Reinforcement Type	Compressive Strength (MPa)		Strength Increase Compared To Control (%)
	Reinforced Concrete	Control Concrete	
Dyneema® Plain (Full Surface)	48.74	36.26	34.42
Friction spun yarn Plain (Full Surface)	40.50	36.26	11.69

Based on the strength increases presented in Tables 4.18 and 4.19, a four-layer reinforcement was applied using un-twisted Dyneema® fabric with a 6 x 6 threads/cm warp and weft density, as shown in Table 4.20. The strength increase rate for the four-layer reinforcement compared to the control concrete was 16.03%. This value is lower than the strength increase rate observed with the three-layer reinforcement. Increasing the number of layers to four resulted in a reduced rate of compressive strength increase.

Table 4. 20: The compressive strength and strength increase rate determined for cylinder samples reinforced with four layers using the selected fabric type.

Fabric Used for Reinforcement and Reinforcement Type	Compressive Strength (MPa)		Strength Increase Compared To Control (%)
	Reinforced Concrete	Control Concrete	

Dyneema® Plain (Full Surface)	38.07	32.81	16.03
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After determining the compressive strength increase rates through reinforcement trials on cylinder samples, three-layer beam reinforcement tests were conducted using the same fabric types to examine the increase in bending strength. The resulting bending strengths and strength increases compared to the control concrete are presented in Table 4.21.

Table 4. 21: Flexural strengths and strength increase rates of beam specimens reinforced with three layers using two selected fabric types.

Fabric Used for Reinforcement and Reinforcement Type	Compressive Strength (MPa)		Strength Increase Compared To Control (%)
	Reinforced Concrete	Control Concrete	
Dyneema® Plain (U Surface)	7.50	7.17	4.60
Dyneema® Twill (A Surface)	9.30	7.17	29.71
Friction spun yarn Plain (U Surface)	8.94	7.17	24.69
Friction spun yarn Twill (A Surface)	9.72	7.17	35.57

Based on the experimental results, it was determined that the most suitable fabric for the study was a single-layer Dyneema® fabric with a 6 threads/cm density and a plain weave. Subsequently, the wrapping of this fabric around the cement for reinforcement applications was initiated, and trials were conducted by increasing the number of wrapping layers.

The compressive strength measurements were performed using cylinder samples. Two different wrapping types were applied for the cylinder samples, the

whole surface and the middle surface. When the compressive strength was examined, it is seen that two loads have been made. As a result of the initial loads, a significant increase in compressive strength could not be achieved. A second loading was made for the samples that were damaged as a result of the first loads. As a result of the second loading, it was found that the samples regained the strength values they received during the first loading, and their compressive strength did not increase again compared to the control samples, but some samples gained strength values close to the control samples. In addition, it has been observed that samples that have been damaged or not damaged during the first loads by making the second loads can also gain strength with the second loading (Table 4.22). It was observed that fabric, mortar and concrete were dispersed in the second loads. This situation is a clear indication of the effect of the strengthening application.

Table 4. 22: Average compressive strengths of reinforced specimens.

Fabric Layer Count	1. Average Compressive Strength at First Loading		2. Average Compressive Strength at Second Loading (MPa)	
	Entire Surface	Middle Surface	Entire Surface	Middle Surface
2	44.98	42.94	28.99	18.45
3	42.61	43.68	40.13	24.52
4	45.38	39.02	42.61	21.63
Control	43.27	-	-	-

The bending strength measurements were made using beam samples. Two different wrapping types were applied on the beams: bottom surface and U surface. When examining the bending strengths of the samples, the positive impact of the reinforcement fabric was clearly evident. As the number of fabric layers increased, the average bending strength increased compared to the control concrete. In addition, changing the way of application from the bottom surface to the U surface provided a higher improvement. In the form of four-layer U-surface application, a strength increase exceeding 68% was achieved on average (Table 4.23). The measured deformation amounts also increased in parallel with the strength gains, with deformation measurements exceeding 5 mm.

These results clearly show that the toughness value (energy absorbing capacity) increases with reinforcement applications.

Table 4. 23: Average bending strengths, average deformation amounts, and average bending strength increases of reinforced specimens.

Fabric Layer Count	Average Bending Strength (MPa)		Average Deformation at Midpoint (mm)		Average Bending Strength Increase (%)	
	Bottom Surface	U Surface	Bottom Surface	U Surface	Bottom Surface	U Surface
2	8.48	8.86	1.27	2.43	15.33	23.40
3	8.45	8.83	1.33	3.54	17.69	22.98
4	8.11	12.07	1.60	5.03	12.95	68.11
Control	7.18		1.25		-	

5. CONCLUSION

The primary objective of this study is to develop innovative, high-performance textile products for textile-reinforced cement-based composites aimed at reinforcing damaged buildings. The research includes the production of various yarns and woven fabrics, the determination of the properties of these yarns and fabrics, and the application of these fabrics in reinforcement.

Initially, the selection and preparation of yarns used in reinforcement fabrics have been explored. Three types of Dyneema® yarns have been examined: untwisted multifilament yarn, twisted multifilament yarn, and cored friction spun yarn.

For reinforcement fabric production, different woven fabric constructions, such as plain and twill weaves, and fabric densities have been evaluated for their suitability in reinforcement applications. Challenges, such as warp yarn slippage and fiber accumulation on the fabric surface, have been addressed through modifications and alternative solutions, such as using PVA yarn wrapping.

Mechanical testing has revealed that Dyneema® yarns exhibited significant performance advantages, particularly twisted yarns, which facilitated smoother weaving and fewer issues compared to untwisted yarns. Fabrics with plain weave construction have been preferred over twill weaves for their stability and effectiveness in reinforcement.

It has been observed that increasing the number of fabric layers in reinforcement applications led to enhanced compressive strength. For instance, four-layer reinforcements with 6 x 6 threads/cm plain weave Dyneema® fabric resulted in a 16.03% strength increase compared to control concrete, which was lower than the strength increase observed with three-layer reinforcements. Additionally, plain weave construction allowed for more homogeneous mortar infiltration compared to other weave types.

Bending strength improvements have been more pronounced with increased fabric layers, and shifting the application from the underside to a U-shaped surface further enhanced performance. A four-layer U-shaped application achieved an average strength increase exceeding 68%, with deformation measurements surpassing 5 mm, reflecting improved toughness and energy absorption.

Based on these findings, the most suitable fabric structure for reinforcement has been determined to be plain weave Dyneema® fabric with a 6 x 6 threads/cm density. Currently, longitudinal testing of full-scale columns with the produced fabrics is ongoing to fully assess their effectiveness.



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ACKNOWLEDGMENTS

First of all, I would like to acknowledge and thank my advisor Prof. Dr. Güldemet BAŞAL and co-adviser Prof. Dr. Sevda ALTAŞ for their support and guidance throughout this thesis work..

I would also like to express my gratitude to Arif ER, who helped me with his experience during the production of fabric samples at the weaving laboratory of the Department of Textile Engineering, Ege University.

I appreciate the constant support of my colleagues and friends Kaya ŞİMSEK and Göktuğ KURT who helped me throughout my thesis and did not spare moral support.

Special thanks to Research Assistant Dr. Cihat YÜKSEL for his invaluable knowledge and support in the field of civil engineering for this study., and to my civil engineer friends Mithat Can BİÇER and Uğur VAHAP for their assistance and exchange of information in the production processes.

Finally, I would like to express my sincere thanks to my family. My mother Nuran MORGÜL, my father Başar MORGÜL and finally my brother Hüseyin MORGÜL, whose support and faith in my academic endeavors are a constant source of motivation for me.

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