Chapter 5

Hybrid Yarn Composites for Construction

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.69034

Abstract

Textile-reinforced concrete (TRC) is a new innovative construction material that leads to light-weight and cost-effective construction. TRC consists of a finely grained cement-based matrix and high-performance, continuous multifilament yarns made of alkali-resistant glass, carbon, or polymer. Using these fibers provides superior mechanical properties and corrosion resistance in comparison with ferroconcrete. The application of epoxy resin coating to the textile materials improves the utilization of mechanical performance and handling properties as well. In recent years, researchers have studied alternative methods because coating process is very detailed and epoxy resin is of high cost. The experimental part of this chapter focuses on the experimental investigation carried out on high-strength concrete reinforced with hybrid yarns. Braiding technology was used to manufacture hybrid yarn from alkali-resistant glass fiber (ARG) and polypropylene (PP) filament. Next step, thermoplastic part of braided yarn was melted on press heating. Finally, TRC was produced from ARG, coated ARG, carbon fiber, coated carbon fiber, and heated hybrid yarns. Although the contribution of the heated hybrid yarn is limited, it is expected that the desired results will be obtained by changes in braiding yarn production and yarn composition ratios.

Keywords: technical textiles, hybrid yarn, composites, buildtech, textile-reinforced concrete

1. Introduction to textile composites for construction

The principal necessities of human are nutrition, clothing, and shelter. The clothing comes after nutrition and has got many selection factors such as social, economic, environmental, and physiological. The main material of clothing is textile. Textiles always have played an important role in protecting from different environmental conditions and making feel comfortable. Nowadays, the textile industry has to accelerate research on innovative and attractive products in many fields from agriculture to space. Recently, construction sector is one of the fields that used these innovative textile materials, and these textile materials are named "Buildtech." Buildtech products are defined as membrane, lightweight and massive construction materials, etc. for engineering and industrial buildings [1].

Construction is improving from the earliest times. At ancient times, people built kinds of buildings to shelter. To reduce cracking and to increase bearing capacity of buildings, they added hairs and vegetables in the mortar. Later with technology, construction materials changed. Different materials were used for each period. In the early period, mortar was used, but later various materials such as wood, stone, marble, and steel were used. Finally, with the discovery of concrete, its use in the construction industry has become widespread [2, 3].

Since 1800s, quick developments in construction materials technology have allowed civil engineers to achieve impressive gains in the safety, economy, and functionality of structures built to serve the common needs of the community [4]. Today, in the construction sector, steel-reinforced concrete is most important, and it is used widely for structural applications. For several decades, textile-reinforced concrete (TRC) has been innovative material for constructions. TRC can be used instead of conventional composite-building materials for many new applications [5]. TRC is a new composite material consisting of a fine-grained concrete matrix and corrosion-resistant high-performance multifilament yarns such as alkali-resistant glass, carbon, basalt, and polymer [6]. These raw materials are used to produce different textile forms for TRC. Those suited for the reinforcement of concrete matrix are yarns, warp knits (plain, circular or three-dimensional), multi-plies (plain or circular), and woven [7]. Thanks to these textile materials, production of TRC leads to thin structural elements with high strength, high durability, and corrosion resistance [8].

In the present architectures and constructions, there is a specific trend toward innovative structures of high-quality materials such as carbon, glass fibers, basalt, and aramid that continuously increase the requirements placed on the construction materials and that demand a continuous development of their properties. Using nonmetallic high-performance fibers as concrete reinforcement allows for the production of thin and light-weight elements with high durability and the potential of economic savings. These advantages together with the high scope of design options given to the architects have made glass-fiber–reinforced concrete (GFRC) a widespread construction material around the world. A disadvantage of the reinforcement with chopped strands (for example, AR-glass or PP) is the partial unorientated distribution of the fibers over the total cross-section, reducing their effectiveness. In contrast to steel reinforcement, AR glass or carbon fibers in the textile can be positioned in almost any direction and afterward nearly perfectly adopted to the orientation of the applied load. It is thus possible to create an extremely effective reinforcement. The use of corrosion-resistant technical textiles reduces concrete covers significantly and thus allows for light weight and thin concrete structures [9, 10].

Glass fiber is widely used in construction since 1950s. The cementitious matrix has highly alkaline environment (pH-value > 12.5), and glass fiber has poor corrosion resistance in a highly alkaline environment. Despite the glass fiber being considered as a reinforcement of cementitious materials for several decades, because of poor alkaline resistance, the limitation of structural applications still remains. For this reason, the alkali-resistant glass fiber (ARG) was preferably designed to reinforce cementitious matrices. Enhanced mainly by a high percentage of zirconia (ZrO_2 > 15% by weight) content, the alkali-resistant glass fiber (ARG) was designed to reinforce cementitious matrices that have been used in construction and civil engineering since the late 1960s. Despite ARG being more resistant to highly alkaline environment than normal glass fiber, many attempts have been made to modify either matrix or fiber by adding fillers or by surface coatings of polymer and carbon layers. In the composites sector, a coating is known as a widespread method of providing corrosion protection in order to improve the durability of engineering structures. For alkali-resistant glass fibers (ARGs), multifunctional sizings are required to provide the surface protection, abrasion resistance, and strength maintenance in the concrete. However, both durability in alkali environment and economic considerations have limited the commercial use of these materials. For enhancing the long-term resistance of glass-fiber–reinforced cement products, it is thus very important to develop an inexpensive and applicable coating to modify the ARG fiber surface and examine how the coatings interact with the surrounding cementitious matrix [11–13].

In the production of TRC, the application of polymer coating to the textile materials improves the utilization of mechanical performance and handling properties as well. Generally, thermoset resin is used as a coating material. Coating process is very long term and tough, and also, cost of coating materials is very expensive. Hence, researchers have searched for alternative methods to provide the surface protection, abrasion resistance, and strength maintenance for textile materials in the concrete.

In this study, hybrid yarn was used in the production of TRC as a reinforcement material. First of all, hybrid yarn was produced with braiding technology. In the hybrid yarn production, while alkali-resistant glass fibers (ARGs) were used as a reinforcement material, polypropylene filament (PP) is used as a matrix material. After production of hybrid yarn was heated in the oven, melted polymer covered alkali-resistant glass fibers (ARGs). Melted hybrid yarns were used in the production of TRC. All TRC samples were tested to see the effect of the hybrid yarn on the strength of the concrete. Information about hybrid yarn technology and braiding technology will be mentioned in the following sections.

2. Hybrid yarn technology

For many years, thermoset and thermoplastic composites are often used to produce advanced lightweight structures. Thermoset prepregs, which were previously a combination of resin and fiber, as preformed materials must be kept refrigerated to interrupt the ongoing curing reaction [14]. Generally, in many composite processing methods, the matrix is added to the fibers at the time of manufacture. By using additives and fillers, it improves the surface quality of the part, alleviates some processing problems and reduces the total cost [15, 16].

In the thermoset composite materials, the curing process requires heat and pressure. To improve its usability, the prepreg is typically stored in a freezer and then cured at a high temperature. In the 1960s prepregs produced necessitated quite high cure temperatures and had very short out-lives; nowadays, it is possible for them to be stored in a freezer, have an out-life of possibly several months and a cure temperature of between 50 and 200°C. Prepregs tend to be epoxy resins reinforced with carbon, glass, or aramid fibers. High-temperature polymer composites are occasionally used as other matrix materials [16].

In thermoplastic polymers, the organic molecular units are bonded together. They differ from thermoset polymers in this way. Thermoplastic composites are preferred for their ability to be formed by heat at low pressure. While thermosets are produced with manual production, the thermoplastic processing techniques are machine friendly and enable short processing cycles [14, 17].

Thermoplastic polymers are divided into two groups of amorphous and semicrystalline polymers according to their molecular structure. While amorphous polymers have randomly oriented molecular chains, in semicrystalline polymers, the chains are symmetric enough to be fitted into an ordered crystalline state. Because of the large molecular chain length, complete crystallinity cannot be obtained, and both crystalline and amorphous regions coexist in the solid. When a polymer is cooled, there are some changes. From above, the melt temperature (T_m) to glass transition (T_g), the chains lose mobility and begin to interact segment by segment. At T_g, the molecular chains are locked in place, and the polymer assumes a "glassy" state. In this case, the molecular orientation is random due to the irregular chain structure. At semicrystalline state, polymers crystallize at temperatures so high from the T_g, regions of amorphous, and crystalline phase coexist [17].

When a thermoplastic polymer is heated above the T_m, polymer melt viscosity reduces, and it melts. Many thermoplastic polymers can be used as matrix materials in textile composites. Generally, polymers having a lower melting temperature are preferred due to their ease in processing and drying. There are many approaches such as co-woven yarns, inter-dispersed fabrics, plied matrix, powder impregnation, and commingled materials, and they are used to impregnate the reinforcing textile structure with the matrix polymer [17]. In this techniques, the formability is improved. The first three techniques require direct flow of the polymer melt into the fiber bed. Powder impregnated and commingled materials have fiber and matrix constituents intimately mingled before the melt impregnation process. This reduces the distance that the resin must flow to achieve impregnation, offering the possibility of a fast wet-out during consolidation [18]. Nevertheless, the production of thermoplastic composites has some technical processing problems. For example, as thermoplastic melt has much higher viscosity than common thermoset resins, it is difficult to obtain homogeneous composite structure. There are some methods to produce homogeneous composite structure, and they are the following:

- Polymer direct melt extrusion or pultrusion that reinforce fibers are pulled through a resin;
- Solvents or low viscosity precursors; and
- Close contact between the fiber and the matrix [14].

Although there are novel thermoplastic composite manufacturing methods such as co-compression molding of textile preforms with a flowable core and overinjection molding of stamped preforms, close contact between the fiber and the matrix is widely used in textile composites [17].

http://dx.doi.org/10.5772/intechopen.69034

2.1. Types of hybrid yarns

Hybrid yarns can be produced with many methods such as ring spinning, commingling, and braiding. These methods provide uniform distribution of matrix and reinforcement fibers as well as reduce the damage to reinforcing fibers [19]. The information on methods will be given following sections.

2.1.1. Ring spinning

Classical ring spinning machines have a pair of rollers for the drafting, twisting, and winding mechanism and can use only one type of fiber to manufacture spun yarns. Present ring spinning machines need some modifications to manufacture hybrid yarns. Generally, core ring spinning on a modified ring frame needs with it special guiding devices and feeder rollers (**Figure 1**). With slight modifications and little investment, this technique can be used to produce hybrid yarns by the core spinning system, and these machines are most commonly used to produce core-spun yarns containing elastane as a core. While one type of fiber is used in classical ring spinning, staple fibers and filaments can be used in core ring spinning [19–21].

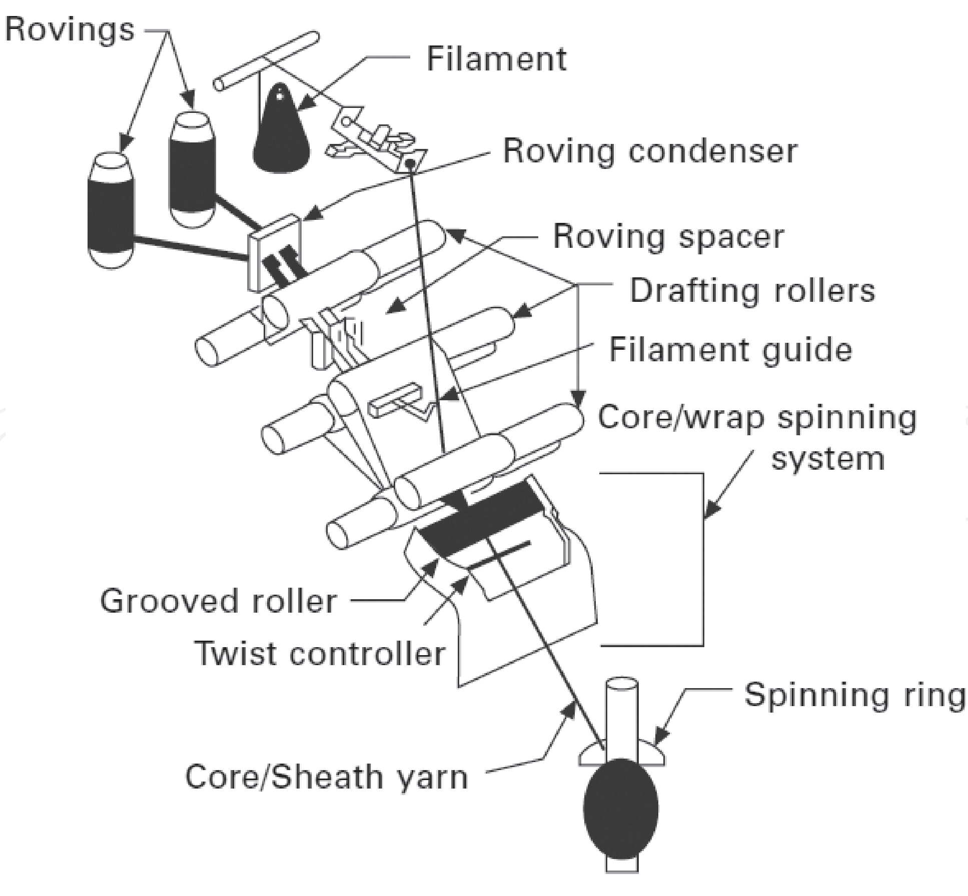


Figure 1. Modified core spinning system [21].

2.1.2. Rotor spinning

As in ring spinning, rotor spinning needs some modifications to manufacture hybrid yarns. In the modified rotor spinning machine, hybrid yarns can be produced by combining staple fibers with filament yarns under varying filament overfeeds. **Figure 2** shows the modified rotor and the diagram of spinning process. In this machine, the staple fiber and the continuous filament were fed into the rotor to produce hybrid yarn. This technology has a tendency to introduce filament misalignment in the core yarn, which is not desirable for composite application [19, 22].

2.1.3. DREF spinning

This spinning system can be used to manufacture core-spun hybrid yarns for thermoplastic composites. In classical DREF spinning, the completely opened fiber strand is brought into engagement with the rotating open end of the yarn by a perforated drum. Attachment and strengthening of the fibers are accomplished by continuously rotating the yarn in the converging region of the two drums. The spinning of the yarn takes place with the help of the rotational movement of the two cylinders, and the friction on the cylinder surface contributes to this [19].

This system can be used to fabricate a hybrid yarn consisting of reinforcement filaments of high-performance fibers in the core and staple fibers of the thermoplastic matrix material such as polyester, poly-ether-etherketone or liquid crystal polymers in the sheath. Hasan et al. studied the application of carbon filament yarn (CFY)–based conductive hybrid yarn as the heating element in a textile-reinforced concrete structure. In order to manufacture this hybrid yarn, they used DREF-2000 spinning technique. Carbon fiber was used as a core, and a mixture of short glass and polypropylene fibers was used as a sheath. **Figure 3** shows friction spinning machine and cross-section of hybrid yarn [19, 23].

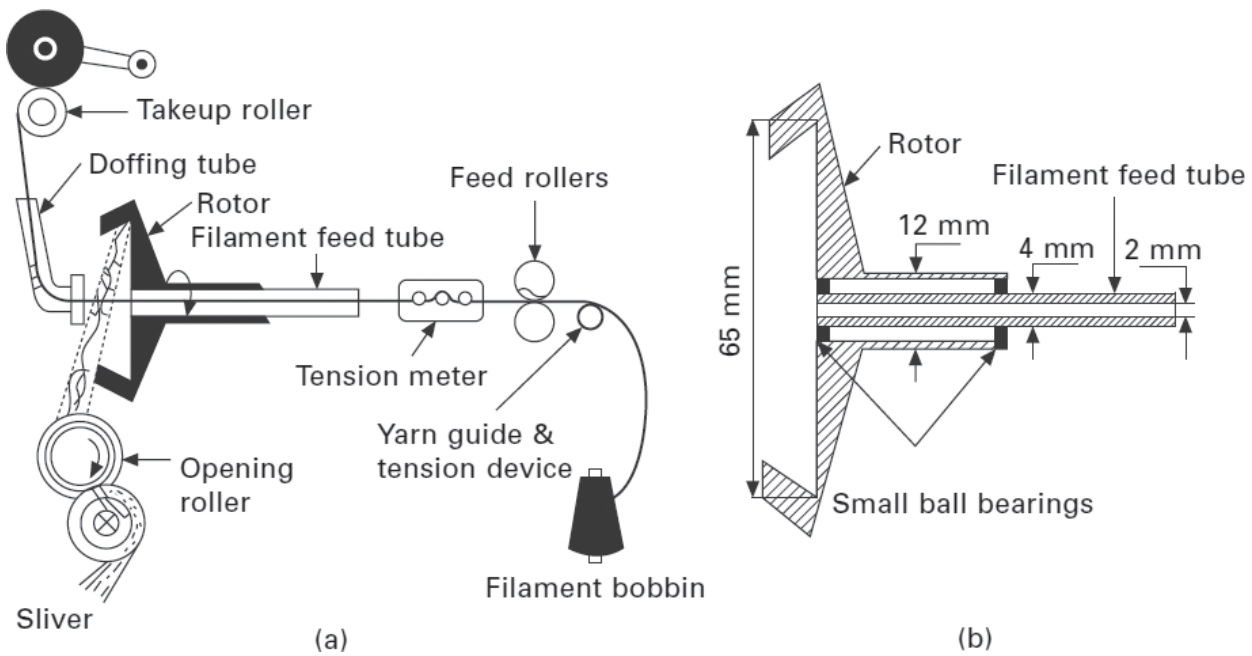


Figure 2. (a) Diagram of spinning process (b) Modified rotor [22].

2.1.4. Wrap spinning

In this system, a roving or a sliver feedstock passes through a hollow spindle without receiving true twist. The continuous filament yarn, which is mounted on the hollow shaft, is passed through the hollow spindle as shown and is wound on the central component (**Figure 4**). Hence, this filament strand is wound around the twistless strand in the core. With some modifications, this system can manufacture hybrid yarn using filament for both core and wrapping. When thermoplastic filament is used as a wrap yarn, during the consolidation process, this component will melt and it becomes part of the matrix [19, 24].

2.1.5. Air-jet texturing

Air-jet texturing is completely a mechanical process, and reinforcing and matrix filaments are combined by air. In this process, the air nozzle is the heart of the air-jet texturing process. Supply yarn is overfed into the turbulent zone, and here, compressed air is guided mainly parallel to the yarn path. This compressed air flow opens up filament bundles and then builds mingling sections (**Figure 5**), as a result, mixed filament yarn is manufactured, but, while filaments mix, some loops occur [19, 25].

2.1.6. Commingling

Like air-jet texturing, in the commingling process, compressed air is used to generate entanglements in and among filaments. In this process, two or more yarns, such as carbon or glass, and a thermoplastic matrix yarn are converted to a single strand. Commingled yarn consists

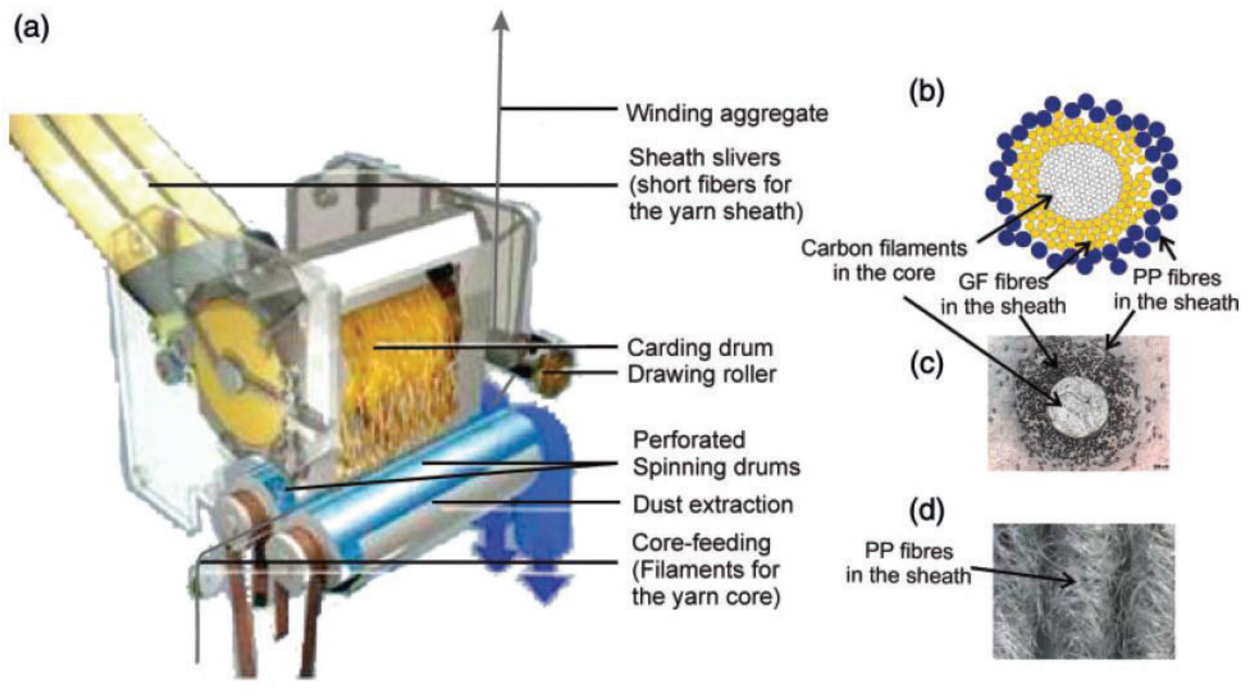


Figure 3. (a) DREF-2000 friction spinning machine (Fehrer AG, Linz, Austria), (b) Sketch and (c) Microscopic image of the cross-section and (d) Longitudinal view of the FS hybrid yarn produced to be used as the heating element [23].

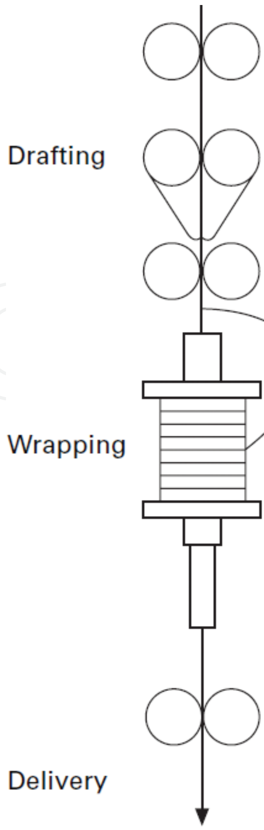


Figure 4. Filament wrap spinning [19].

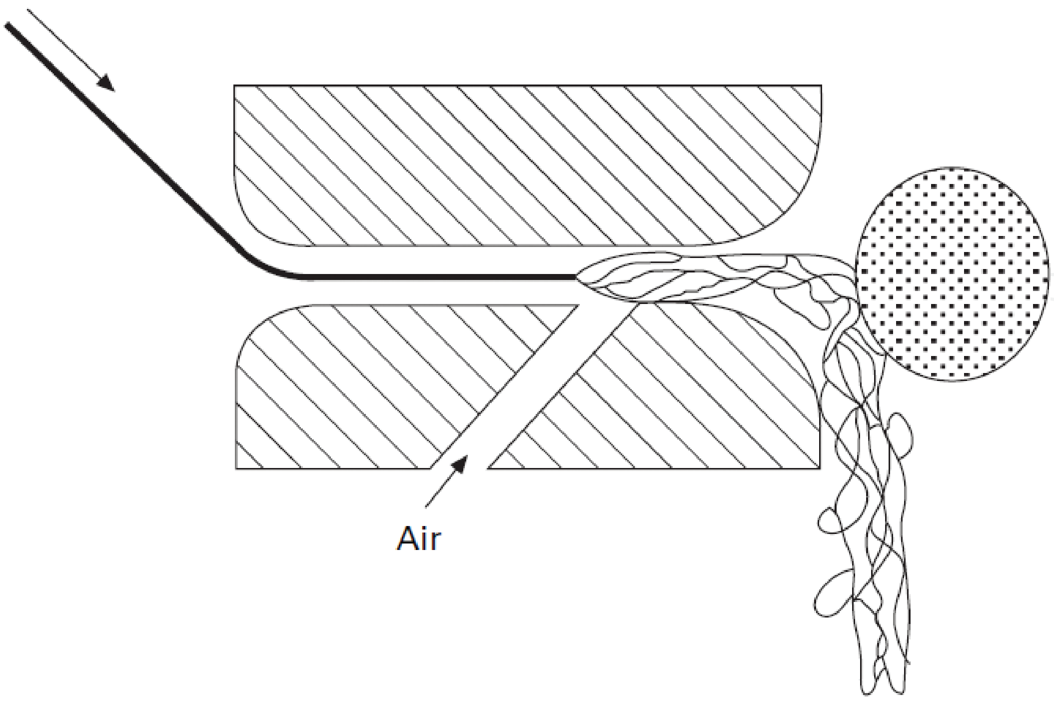


Figure 5. Air-jet yarn texturing [25].

of blended two parts combination, reinforcing filament yarn and filament yarn spun from thermoplastic polymers. In the beginning, the multifilament yarns are scattered by compressed air, and then they are often mixed with each other in parallel. Unlike air-jet texturing, loops do not occur, and generally, filaments are parallel to each other (**Figure 6**). Thanks to the changes in main production parameters such as degree of overfeeding, production speed, and air pressure, it can be manufactured as a hybrid yarn in the desired filament distribution. It is possible to obtain a homogenous distribution of reinforcement and matrix, and this reduces the mass transfer distance of the matrix during processing. In this way, a fast and complete impregnation of the reinforcement filaments is possible [19, 25, 26].

2.1.7. Parallel winding

In this simple process, the two components of the hybrid yarns are brought together side by side, as shown in **Figure 7**. Parallel winding is also called tape winding or the side-by-side technique. In this process, the continuous reinforcement filaments and the thermoplastic filaments are combined in the form of a band. Then, after the heating process, this tape is converted to a composite material [19, 24].

2.1.8. Stretch breaking

In this process, hybrid yarns consist of discontinuous thermoplastic fibers and filaments. They are brought together into a well-oriented coherent bundle by the insertion of a degree of twist. Thanks to this technology, a broken fiber feed on one or two tows of high-modulus filaments such as carbon or glass and also produces highly consistent yarns with minimal fiber damage. When heating is applied, the composite structure is formed by melting the thermoplastic structure [19, 24].

2.1.9. KEMAFIL technology

This technology has been developed in Germany for geotextiles. In this technology, a type of circular knitting machine is used to manufacture hybrid yarn. In this machine, a parallel

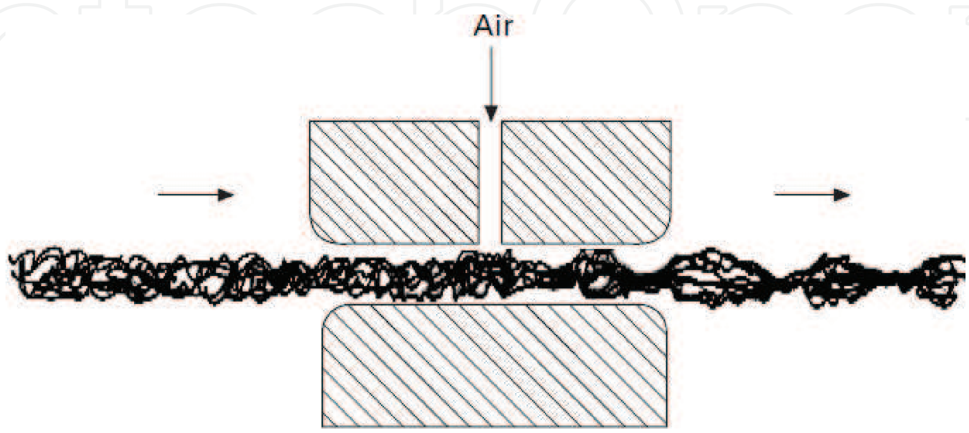


Figure 6. Hybrid yarn by commingling process [19].

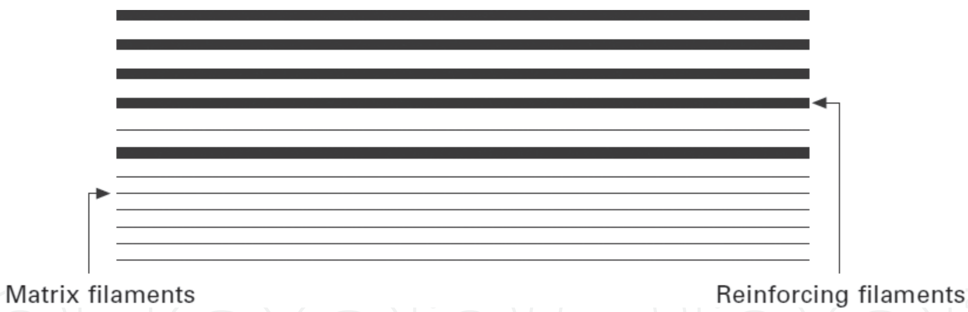


Figure 7. Structure of side-by-side hybrid yarn [19].

arrangement of matrix fibers is surrounded by parallel reinforcing filaments. In this hybrid yarn, while the core consists of matrix and reinforcing filaments, the knitted sheath consists of only matrix fibers [19, 24].

2.1.10. Schappe technology

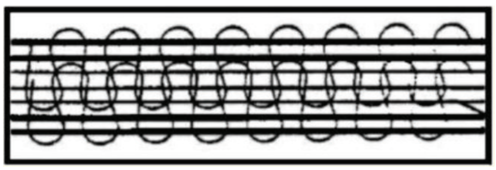
Schappe technology is same as stretch breaking. This technology is used to obtain more bulky and higher tenacity hybrid yarn from long fibers. These types of hybrid yarns are composed of a mixture of discontinuous reinforcing and matrix filaments surrounded by continuous matrix filaments. As this consists of transforming the continuous filaments put on top of long fibers, this technique removes the weak points of the fibers [19, 24].

2.1.11. Braided yarn

Braiding has been used since 1800s to produce textile fabrics and is generally used for producing narrow rope-like materials. In this technology, three or more strands of filaments or yarns are interlaced diagonally like in a Maypole dance. The filament bundles forming the braid are combined in a manner similar to the formation of the ribbon to form the braided yarn. In this way, tubular woven structure occurs. Researchers have focused braiding technology to meet new demands in composite production [27, 28]. Details of braided yarn and its production are discussed in Section 3.

2.2. Fiber distribution in hybrid yarns

The type of hybrid yarn production technique is very important on the fiber distribution in the hybrid yarn. The homogeneity of component fiber distribution within the matrix is strongly dependent on the hybrid yarn structure. Fiber distribution is influential in the quality of the composites, as it will affect the flow distance of thermoplastic polymer when heat is applied. When they are ranked according to the flow distance, the flow distance increased in the order of Schappe yarn, commingled yarn, Kemafil yarn, side-by-side yarn, and lastly, friction spun yarn. This means that the best degree of mixing of reinforcing and matrix are Schappe and commingled hybrid yarns fibers. Hybrid yarn structures are shown in **Table 1** [19].

Hybrid yarn structure	Position of performance filaments
	**Ring core-spun yarn (RS)** Performance filaments in core and covered spun fibers in a twisted form
	**Rotor core-spun yarn (ROS)** Performance filaments in core and covered spun fibers in a wrapped form
	**DREF core-spun yarn (DF)** Parallel arrangement of performance filaments in core and covered spun fibers
	**Wrap yarn (WS)** Parallel laid fibers in core and covered by performance filaments
	**Air-jet textured yarn (AT)** Thermoplastic filament and performance filaments are interlaced forming loop structure
	**Commingled (COM)** Thermoplastic filaments and performance filaments in a mingled form
	**Parallel winding (SBS)** Parallel arrangement of performance filaments and thermoplastic filaments
	**Stretch break (SB)** Stretched break thermoplastic filaments covered by performance filaments
	**Kemafil technology (KEM)** Parallel arrangement of thermoplastic filaments surrounded by parallel performance filaments in the core, sheath in continuous filament in a knitted form

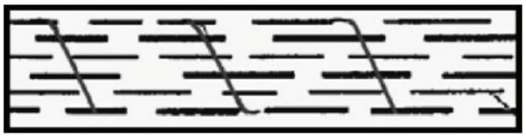
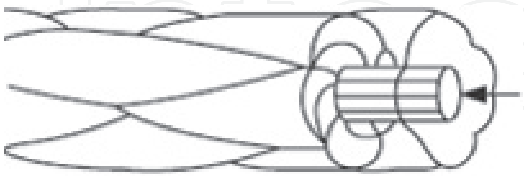
Hybrid yarn structure	Position of performance filaments
	**Schappe technology (SCH)** Mixture of discontinuous performance material and fibers surrounded by thermoplastic filaments
	**Braiding technology** Filament or yarns in core and covered by performance filaments

Table 1. Hybrid yarn structures based on production method [19, 24].

3. Braiding technology

In composites manufacturing, the molten thermoplastic must flow through the capillaries between the reinforcement filaments. Theoretically, this can be achieved with a commingling method. In our previous studies, this method was tried, and some results were realized. It produced hybrid yarns approximately 1100 tex from 640 tex AR-glass roving and 400 tex polypropylene (PP) filament. In textile reinforcement concrete, generally 2400 tex or more linear density is used as a reinforcement material. In our study with approximately 1100 tex, it could not get a good homogeneity of fiber distribution. A further development of higher linear density with homogeneous fiber content is necessary. Therefore, the braiding yarn was used in this study as a new approach in order to obtain hybrid yarn for TRC production. Also, braiding technology offers minimum or no damage to the reinforcement fiber bundles, when compared to using commingled yarns.

3.1. Introduction to braiding technology

Braiding has been used for 200 years to produce textile fabrics. In this process, three or more threads are interlaced diagonally to the product axis [28, 29].

As the threads pass diagonally, they make an angle between 1 and 89° with the product axis of the yarns, usually within the range of 30–80° (**Figure 8**). This angle is called the braiding angle and is the most important geometric parameter of braided structures [29].

It is possible to produce a thicker, wider, or stronger product or cover some profiles in braiding technology. These products can be linear products (ropes), curved or plane shell, or solid structures (one, two, or three-dimensional (3D) fabrics) with constant or variable cross-section and of closed or open appearance. Researchers have focused braiding technology to meet new demands in composite production [28, 29].

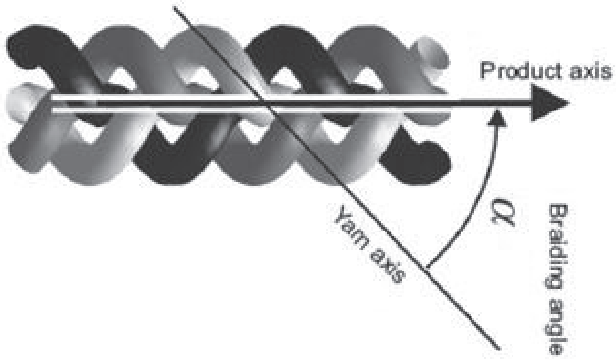


Figure 8. Structure of braided yarn [29].

3.2. Machine and product classification

There are several different classifications of the braided processes, machines, and products. Generally, braided products of maypole braiding machines are divided into two main groups: Braids with constant cross-section and variable cross-section form. While there is flat braiding, tubular braiding, and form braiding for braids with constant cross-section, there are only 3D Braids for variable cross-section form. Each group has normal or biaxial braiding and triaxial braiding types. The classical and mainly used braiding machines are known as maypole braiding machines. This name will always be used where these machines have to be distinguished from the other (spiral, lace) braiding machines. Details of these classification are mentioned in the following sections. In the future, it is expected that with the increasing speed of electromechanical drives, maypole braiding machines with switches (3D braiding) will be able to work continuously [29].

3.3. Basic principle

Braiding has been used for many years in different application areas such as braiding of yarns, flowers, and hair. The application areas for braided products are widespread such as medical items, electric cables, ropes, laces, the huge ropes, and tubes used in the marine oilfield sector. Also, use of braids is growing in the production of fiber-reinforced composites. All the products are manufactured in the same way, i.e., by the interlacing of yarns at an angle of about 40–60° to the main product axis. **Figure 9** shows the principle of hand braiding for a simple braid of three yarns. Initial structure (**Figure 9(a)**) is transformed to the interlacement in two steps:

- In the left two yarns, the outer left yarn goes over the next one (**Figure 9(b)**);
- In the right two yarns, the right yarn goes over the left next nearest yarn (**Figure 9(c)**), and it repeats in the same way [29].

3.4. Flat braiding

Flat braiding structures can be obtained when basic braiding is applied to more yarns, e.g. 5, 7. Flat braiding principle is seen in **Figure 10(a,b)**. In this case, at the first step, all left pairs interlace

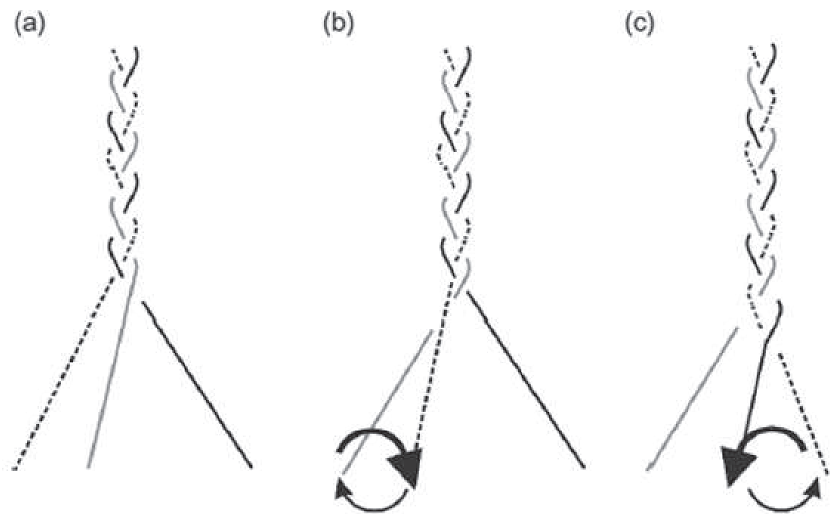


Figure 9. Principle of hand braiding with three yarns [29].

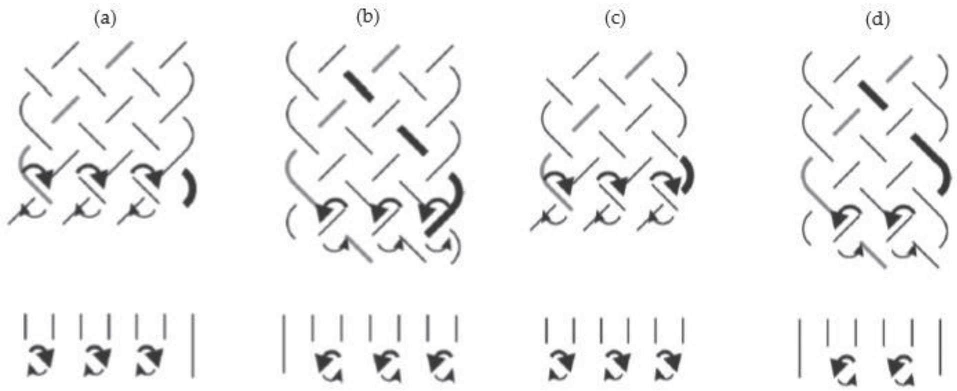


Figure 10. Hand braiding of odd (here seven) yarns (a,b) and of even (here six) yarns(c,d) [29].

so that the left goes over the right, and in the second step, all right pairs interlace so that the right yarn goes over the left [29].

Flat braiding is possible for both odd and even numbers of yarns. **Figure 10(c,d)** shows the sequence in the case of six yarns: at every second step, yarns from both the left and right sides stay and wait, while when using an odd number of yarns, only one yarn per cycle stays unused during the interlacement [29].

3.5. Tubular braiding

In this system, even number of yarns arranged around a circle interlace for production of tubular braids or ropes (**Figure 11**). The sequence of steps in this case is the same as for the flat yarn. In order to produce a regular structure, all yarns have to be kept under constant tension during the braiding process [29].

The interlacing sequence in the case of tubular braiding is same in flat braiding, but unlike flat braiding, all the yarn ends are located around a circle (**Figure 12**). The process can be described as follows:

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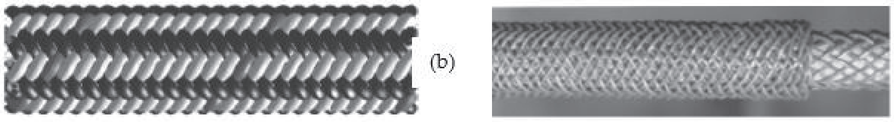

Figure 11. Tubular braids (rope). (a) Geometrical model and (b) Single (upper part) and Tripple (over-) braided part [29].

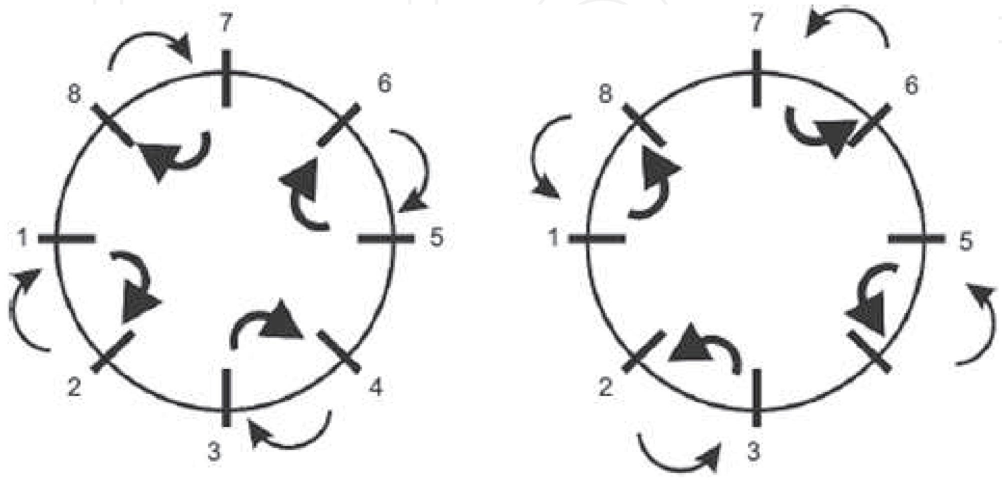

Figure 12. Sequence for tubular braiding [29].

- Interlacement of the left yarn over the right yarn in each pair (the yarn at position 1 goes over the yarn at position 2 and the yarn from position 2 goes to position 1, but interlacing under the first yarn; the pairs are 1–2; 3–4; 5–6; 7–8).
- After shifting the positions (the pairs become 8–1; 2–3; 4–5; 6–7), the right yarn goes over the left yarn in each pair [29].

In tubular braiding, the beam is slowly covered from the top down. In braiding terminology, the beam is called the core (if it had a regular form) or the mandrel (if it had a more complex geometry), and this braiding system is used today for overbraiding of profiles with carbon or glass fiber composites for aerospace, cables, high pressure ropes, etc., for automotive and other applications [29].

3.6. Biaxial and triaxial braids, inlay yarns

Inlay yarns can be put in between the core and the yarns. These are named differently in each every different application areas, e.g., middle ends, inlays, and triaxial braids (**Figure 13**) [29].

Inlay yarns can be inserted into all kinds of braided structures; however, the core or the mandrel requires a hollow structure and is mainly used in tubular braids (**Figure 14**) [29].

3.7. Industrial maypole braiding

In industrial braiding, the machine dancer element is called a carrier, and the path of the carrier is called the track. If the motion of the dancers/carriers is analyzed carefully, it can be seen that all dancers/carriers in one direction are following the same track, while the dancers/

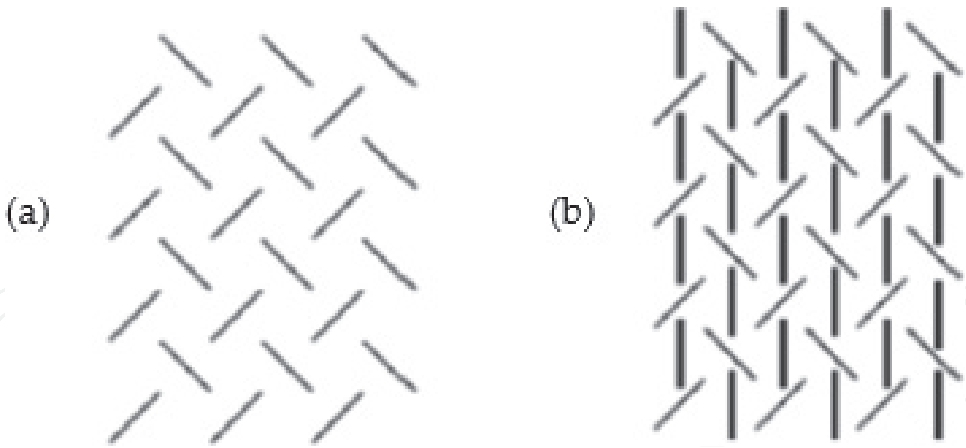

Figure 13. (a) Normal (biaxial) braids and (b) Braids with inlay yarns (triaxial) [29].

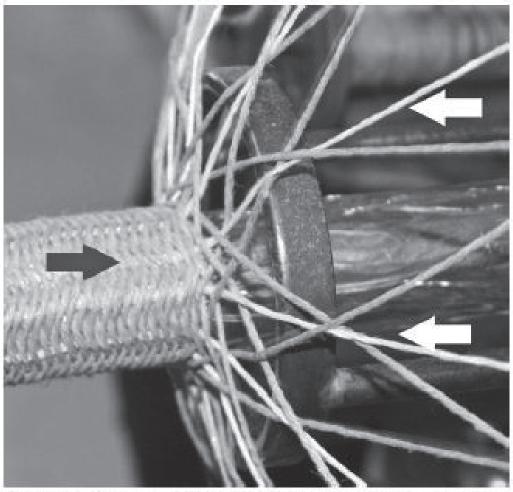

Figure 14. Tubular braid with core and inlay yarns (triaxial) [29].

carriers in the opposite direction follow the opposite track. Hence, for tubular braiding, there are two tracks and two systems of carriers [29].

The path of the motion is determined by the track, but the carriers are moved forward by the horn gears (**Figure 15**). At the beginning of the process, all outer ends of the yarns are connected together at the braiding point. When the carriers start their motions, the yarns interlace together. With this move, the next piece of braid is built at the braiding point. Finally, the braid produced is finally pulled out with the help of a take-off system [29].

3.8. Form braiding and 3D braiding

For different applications, such as thicker braided products of square or other cross-sectional type is required. For example, gaskets or fiber-reinforced composites can be manufactured with these products. In this case, the braiding process is called packing braiding, or 2.5D braiding (2.5D means more than the two dimensions of length and width, but less than

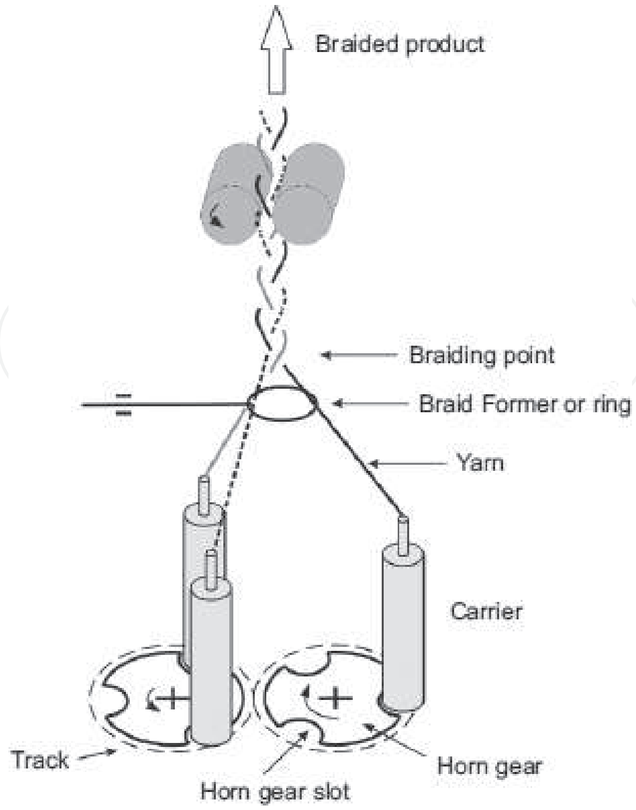

Figure 15. Principal construction of maypole braiding machine [29].

three dimensions), or alternatively, 3D braiding (due to the braided product having thickness in all three directions). However, according to some classifications, they may also be named 3D, 4D, etc., braiding, but D means "diagonal" here. In the new generation of braiding machines, they are controlled by a computer, and the track is not constant. The carrier can change its motion and can travel along a set of connected curves, and the selection of the next curve can change dynamically during the braiding process. Thanks to diversity, the braids do not have a constant cross-section, they are called 3D braids, and the process itself is 3D braiding [3, 29].

3.9. Applications of braiding yarns

The application of braids is various from medical items to electric cable. Also, use of braids is growing in the production of fiber-reinforced composites [3, 29].

If we summarize, we can classify the application fields as follows:

- Clothing: women's and men's wear, outwear, underwear, shoes (laces).
- Sports: aerial sports (starting rope for glider pilots), sailing (anchor ropes, sailcloth), mountain climbing (ropes), camping (tent ropes), fishing, tennis.
- Home textiles: curtains (laces, cords), decoration threads.
- Medical: surgery (blood veins, sewing threads, catheter), prostheses, tapes for orthopedics.

- Machine engineering: fiber-reinforced materials, package seals.
- Civil engineering: fiber-reinforced concrete.
- Traffic: fiber-reinforced materials for aircraft and car construction, track vehicles, and shipping.
- Electrical terotechnology: cables, insulation.
- Household: packaging, clothesline, do-it-yourself requirements [3, 29, 30].

3.10. Braiding technology in future

- Replacements of mechanical controls of braiding machines by electronic controls will reduce setup times.
- In future decades, even if braiding machine by electronic control will be used, mechanical carriers will surely continue to be used in a large number of applications.
- Braiding machines for the production of 3-D braids to obtain larger and more complex cross sections will be developed, and they can be used for nearly every application.
- Mathematical models between machine controls and the position of threads in the braid will be defined [3].

4. Experimental

Experimental study is focused on use of braiding yarn for textile-reinforced concrete. Hybrid yarn was produced with using braiding method. Hybrid yarn to be used as reinforcement has a unique combination of reinforcement and matrix component that was produced using a tubular braiding machine consisting of 16 spindles (**Figure 16**). Hybrid yarn can be thought of as a single yarn, although it is composed of two components. Continuous AR-Glass roving was used as the straight inserted axial fibers, and matrix fibers (PP fibers) were braided around the reinforcing AR-Glass roving.

AR-Glass fiber roving (Cem-FIL® 5325 from OCV Reinforcements) and polypropylene (PP) filament yarn (Aker Textile Yarn) were used to produce hybrid yarn with braiding method. The linear density of AR-Glass is 2400 tex, and the linear density of PP filament is 666.6 dtex. To produce hybrid yarn with braiding method, 1-filament AR-Glass and 16-filament PP were used. Yarn linear density was measured according to ISO 2060. The linear density of hybrid yarn, its components, and other reinforcing components are given in **Table 2**.

After the production of hybrid yarn, a hot compression molder was used to fabricate continuous fiber-reinforced thermoplastic composites. Matrix fibers were melted by heating at appropriate molding temperatures and become the matrices for the fiber-reinforced composites that easily wet out the reinforcing AR-glass roving. **Figure 17** shows the view of hybrid yarn before and after heating.

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Figure 16. Braiding machine.

Yarn	Linear density (tex)
AR-Glass roving	2400
AR-Glass roving (coated with epoxy resin)	3840
Polypropylene (PP) filament	66.66
Hybrid yarn	3430
Carbon	1600
Carbon (coated with epoxy resin)	2560

Table 2. Linear density of hybrid yarn and its component.

Before and after heating, the cross-section of hybrid yarn was investigated on a microscope with 40× (**Figure 18**). It was observed that while structure of hybrid yarn was a bit loose before heating (a, b), it turned into compact structure after heating (c, d).

After hybrid yarns were prepared, coated AR-glass fibers were prepared to compare with hybrid yarn and uncoated AR-glass fibers. Epoxy resin (SR 8500/ SD 8605 from Sicomin) was applied to AR-glass fibers with roller coater. After coating, all samples were preheated and fixed at appropriate temperature and time. **Figure 19** shows the view of AR-glass fibers before and after coating.

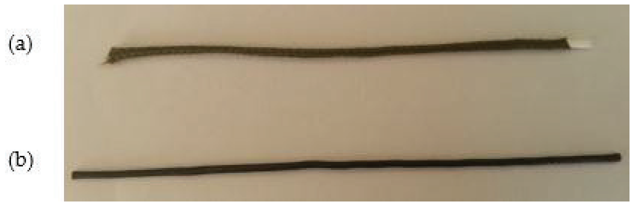

Figure 17. (a) Hybrid yarn before heating (b) Hybrid yarn after heating.

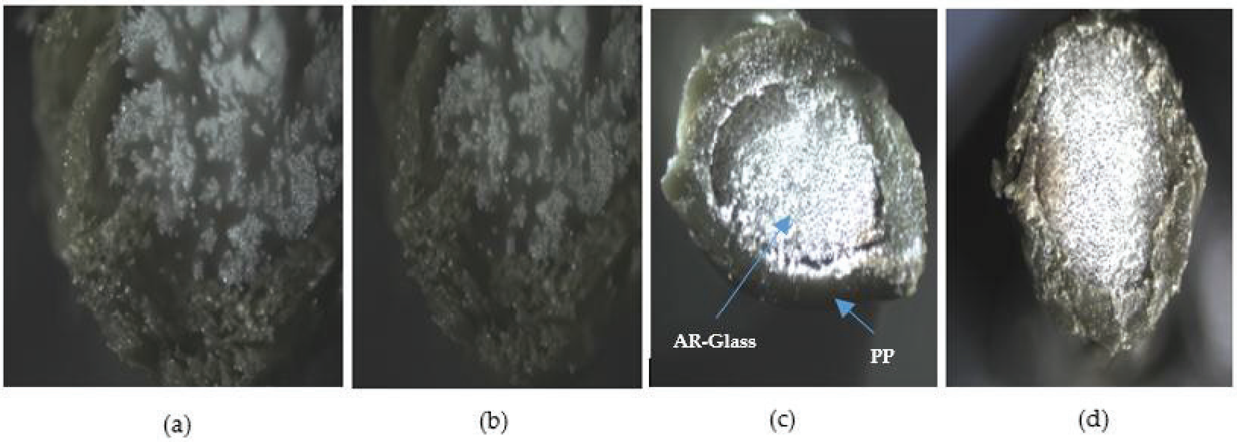

Figure 18. Cross-section of hybrid yarn before heating (a, b), Cross-section of hybrid yarn after heating (c, d).

Figure 19. (a) Uncoated AR-Glass fibers (b) Coated AR-Glass fibers.

Prepared textile materials were placed in the mold for flexural test. For each sample, five yarns were placed in the mold along the long edge, and the distance between each yarn was set to 1 cm. The yarns were placed at a distance of 3 mm from bottom of the sample (**Figure 20**).

After all the textile components were prepared, second component for TRC which is concrete was prepared as shown in the mix proportions in **Table 3**.

The mixtures were batched in the vertical axis concrete mixer (**Figure 21**). The cement and fly ash were dry mixed for 1 min. This was followed by the addition of fine-grained aggregate, water, and the superplasticiser, with a mixing time of 5 min. After pouring the mix into oiled molds, a vibrator was used to decrease the amount of air bubbles. The specimens were demolded after 1 day and then placed in a curing room in the special pool which its water temperature is 20°C for 27 days of curing according to TS EN 12390-2 standard. For 12 h prior to the tests, the specimens were allowed to air dry in the laboratory.

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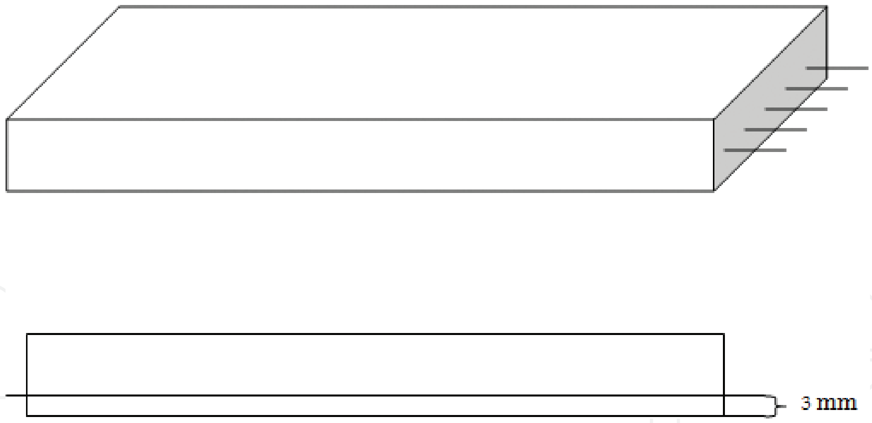


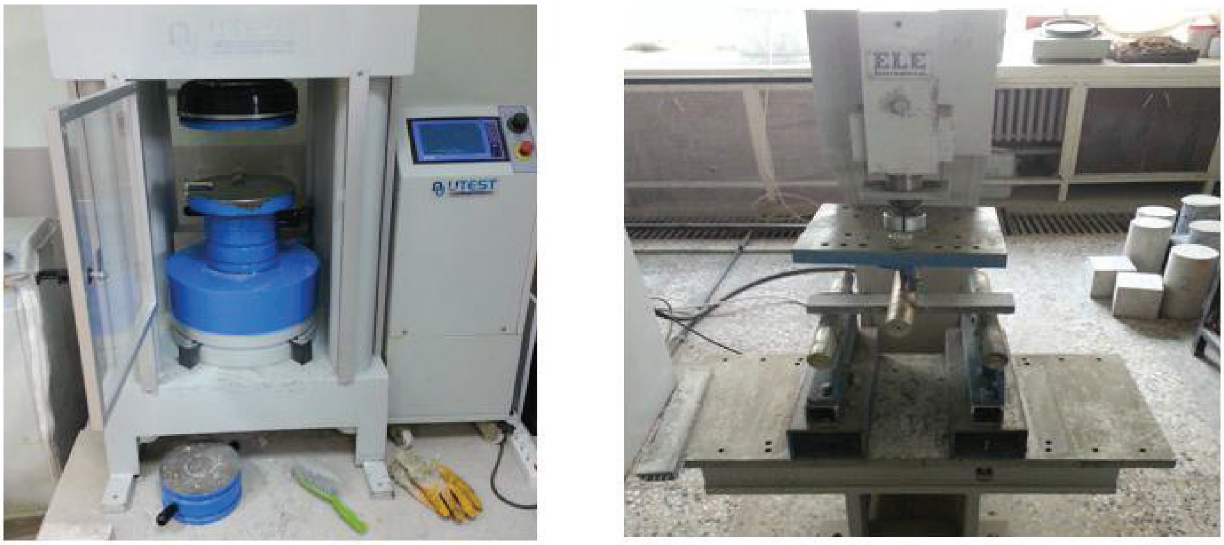
Figure 20. Yarn position in the TRC sample.

Mix proportions	
Cement CEM I 42.5 R (c)	480 kg/m³
Fly ash (f)	240 kg/m³
Water (w)	284 kg/m³
w/b*	0.39
Superplasticizer	1.5% b. m. of binder
Siliceous fines (0–0.3 mm)	642 kg/m³
Siliceous sand (0.2–0.5 mm)	503 kg/m³

*w/b = w/(c + f)

Table 3. Mix proportions of fine grained concrete.

Figure 21. Concrete mixer.



(a) (b)

Figure 22. (a) Compression test machine (b) Flexural strenght test machine.

For the prepared mixture, eight specimens (three 150 × 150 × 150 mm cubes for compression test and five 325 × 50 × 20 mm beams for three-point loading flexural test) were prepared. The compression tests were carried out in the UTEST compression test machine (Type UTC-5750) (**Figure 22(a)**) at a loading rate of 4 kN/s on the 150 × 150 × 150 mm cubes according to the requirements of TS EN 12390-3 standard. The three-point loading flexural tests were carried out in ELE flexural test machine (Model 37-6330; **Figure 22(b)**) at a loading rate of 0.4 kN/s on the 325 × 50 × 20 mm beams according to the requirements of TS EN 12390-5 standard. The mean values of the test results were shown in table at next section.

5. Results and discussion

The mechanical properties of the concrete were measured with a compression test to see the strength of concrete used in the TRC production. The average compressive strength (28 days) of a cube specimen (150 × 150 × 150 mm) was taken as 52.3 MPa. This result is good for conventional concrete. This concrete mix was used in the production of all TRC samples, and different materials were used as a reinforcing component.

In this study, only AR-glass roving was used to manufacture hybrid yarn with braiding technology. There is only AR-glass roving inside the braided yarn, and it is covered with PP filaments. To see the effectiveness of coating, carbon fiber (1600 tex from DOWAKSA) was used to produce TRC. The results of 3-point loading flexural test can be seen in **Table 4**.

As seen in **Table 4**, each reinforcement material contributes to the flexural strength of the concrete. Commonly used AR-glass roving and carbon filaments in concrete reinforcement have contributed to flexural strength, 41.19 and 146.57%, respectively, according to without reinforcement. As expected, the epoxy resin coating also has contributed to flexural strength

TRC samples	F (MPa)
Pure concrete	10.05
Reinforced with uncoated AR-Glass roving	14.19
Reinforced with coated AR-Glass roving	25.32
Reinforced with heated hybrid yarn	15.85
Reinforced with uncoated carbon fiber	24.78
Reinforced with coated carbon fiber	40.81

Table 4. Results of 3-point loading flexural test.

according to reinforcement with AR-glass roving and carbon filament, respectively, 78.44 and 64.69%. Heat-treated hybrid yarn reinforcement has contributed to a flexural strength of 57.71% according to without reinforcement. While reinforcement with epoxy resin coating has contributed to the flexural strength of 78.44%, reinforcement with heated hybrid yarn has contributed to flexural strength of 11.70% according to reinforced with AR-Glass roving. In this study, as it is known, it was seen that the epoxy resin coating provides a significant contribution. It is possible to evaluate the use of heated hybrid yarns produced by braiding technology in the production of TRC though it has contributed less than epoxy resin, since the epoxy resin cost is high and epoxy resin coating process is long and difficult.

6. Conclusion

In the experimental part of this study, the braiding method for using of TRC was investigated. Tubular braiding technique was applied to produce hybrid yarns using AR-glass roving as the core reinforcement fibers and PP fibers as the matrices around AR-glass roving. At the next step, these hybrid yarns were heated, and they were used for TRC production. All prepared samples used flexural strength test. When all test results were examined:

- Reinforcing materials such as AR-glass roving, carbon filament, and heated hybrid yarn have been found to increase the flexural strength.
- Carbon filament is better than AR-glass roving to reinforce the concrete for higher flexural strength.
- As expected, the epoxy resin coating also has contributed to high flexural strength according to reinforcement without coating.
- Also, the application of epoxy resin coating to the textile yarn improves the utilization of mechanical performance and handling properties as well.
- Although the contribution of the heated hybrid yarn is limited, it is expected that the desired results will be obtained by changes in braiding yarn production and yarn composition ratios.

Acknowledgements

This research is supported by "Scientific Research Projects Governing Unit of Çukurova University" with project number FDK-2016-6682. We would also like to thank KORD Industrial Rope and Yarn Industry and Trade Inc.—for hybrid yarn production; ÇİMSA Cement Industry and Trade Inc.—for their materials and laboratory; and Çukurova University Civil Engineering Department—for their laboratory.

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